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Design of MV Switchgear Used for Laboratory Purpose

Návrh VN rozvodny pro laboratoř

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- Design of operational principals and interlocking concept
- Calculation of basic protection setting parameters
- Evaluation of the results

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o Protection product guides

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

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Declaration Made by the Student

I hereby declare that this master's thesis was written by myself. I have quoted all the references I have drawn upon.

Date: 13.05.2020

Signature: ____________

Abstrakt

Tato diplomová práce se zabývá podrobným návrhem VN rozvodny, která vzniká ve spolupráci s firmou ABB pro výukové a výzkumné účely katedry elektroenergetiky při VŠB-TU Ostrava.

Práce obsahuje jednotlivé dílčí činnosti, uskutečněné v rámci návrhu. První část obsahuje teoretické aspekty rozvoden, druhá část pak popisuje v korcích vlastní návrh rozvodny. Pozornost je zaměřena zejména na návrh řídících obvodů rozvodny a ovládacího rozváděče. Popsány jsou také funkce systémů pro blokování a jištění.

Klíčová slova

Klíčová slova: ovládací panel, rozvodna, rozváděč, primární výstroj, jistič, IED, chránění, koncepce blokování, obvod, relé.

Abstract

Within the cooperation between Technical University of Ostrava and ABB European operation center in Ostrava was completed a project of detailed design of the substation that should serve in purpose of science as a laboratory unit.

This work contains a description of the main stages completed during the execution of the project. The first half is devoted to the theoretical aspects necessary for this project, and the second half considers all the main design steps directly. The main attention is paid to the design of the substation control system, namely, the development of the control cabinet. The basic aspects of the interlocking concept and protection functions were considered as well.

Keywords

Keywords: control cabinet, switchgear, substation, primary equipment, circuit breaker, IED, protection, interlock concept, circuit, relay

Table of contents

List of symbols and Abbreviations used

ABB - Asea Brown Boveri;
AC – Alternating Current;
CP – Control Cabinet;
CT – Current Transformer;
DC – Direct Current;
DTT – Data Type Template;
ELDS - Distribution Solutions business line;
GIS – Gas-Insulated Substations;
GOOSE – Generic Object-Oriented Substation Event;
GOST – Gosudarstvenii Standart (Rus), SUST – State Union Standard (Eng);
HMI – Human Machine Interface;
HSR – High-Speed Relay;
HV – High Voltage;
ICD – IED Capability Description;
IEC – International Electrotechnical Commission;
IED – Intelligent Electronic Device;
IEEE – Institute of Electrical and Electronics Engineers;
IT – Instrument Transformer;
LED – Light-Emitting Diode;
MCB – Miniature Circuit Breaker;
MV – Medium Voltage;
OEM – Optical Ethernet Module;
PC – Personal Computer;
PRP – Parallel Redundancy Protocol;
RJ – Registered Jack;
RS – Recommended Standard;
RTD – Resistance Temperature Detector;
RTU – Remote Terminal Unit;
SCADA – Supervision, Control and Data Acquisition;
SCD – Substation Configuration Description;
SCL – Short Circuit Location;
SF_6 – Sulfur Hexafluoride;
SLD – Single-Line Diagram;
SSD – System Specification Description;
TCP – Transmission Control Protocol;
TCS – Trip Circuit Supervision;
USB – Universal Serial Bus;
VSB – Vysoka Skola Banska;
VT – Voltage Transformer.

List of Images and Charts

Introduction

This work is devoted to describing the main steps undertaken in the implementation of the project for the design of the substation which will be used as a laboratory installation. According to the initial design specification, the designed substation must ensure sustainable operation at several different voltage levels, meet modern standards in the field of electric power engineering, and meet all safety requirements.

The first chapter contains a basic theory about the types of substations, recommendations for the design, as well as an analysis of the main types of circuits used for modern switchgears.

The second chapter is devoted to theoretical questions about primary electrical equipment, as well as basic questions of relay protection and communication for a substation.

The third chapter contains a technical specification that defines the main points to be completed in the course of the project, as well as the definition of the main initial parameters of the substation.

The fourth chapter contains the calculation of short-circuit currents.

The fifth chapter is devoted to the selection of basic electrical equipment based on the calculations given in the fourth chapter.

The sixth chapter is entirely devoted to the development of the substation control system, in particular the control cabinet. The aspects of the interlocking concept are considered, and the detailed design of the substation's secondary circuits is completed.

1 Basic Theory about Switchgears and Design Procedure

1.1 Switchgear types

The aim of this part is to discuss the most used types of switchgears which can be seen almost in each distribution network, based on theory define the type for designed switchgear. A switchgear assembly has two types of components:

- Power conducting components, such as switches, circuit breakers, fuses, and lightning arrestors, that conduct or interrupt the flow of electrical power;
- Control systems such as control cabinets, current transformers, voltage transformers, protective relays, and associated circuitry, that monitor, control, and protect the power conducting components.

One of the basic functions of switchgear is protection, which is interruption of short-circuit and overload fault currents while maintaining service to unaffected circuits. Switchgear also provides isolation of circuits from power supplies. Switchgear is also used to enhance system availability by allowing more than one source to feed a load.

Depending on the type of switchgear there are several methods of construction of substation. Nowadays there are four most common used types: Open-air; Metal enclosed; Metal-clad; Gas insulated.

1.1.1 Open air substations

The main principle of open-air substation is that all primary equipment such as circuit breakers, disconnectors, current transformers, voltage transformers, busbars, etc. is mounted and interconnected separately, where atmospheric air creates and provides the main insulation material.

The insulators must be designed with sufficient capability to withstand for many years all environmental conditions, e.g. rain, snow, ice, wind, temperature drops, dust pollution, lighting strokes, transient effects during switching operations to prevent dielectric breakdown to earth or between phases.

This is very important requirement and it requires relatively large clearances, and, in consequence, open-air substations tend to cover large ground areas. [1]

Figure 1 – Open-air substation (on photo: 115 kV/12.47 kV outdoor steel Poker Lake Substation)

1.1.2 Metal enclosed

In metal-enclosed arrangement all primary equipment and associated components are contained in metal enclosure which is earthed. They are cable connected and have per-bay basis.

The main disadvantage of this arrangement that there is no segregation inside the panel. That means that fault on any device can easily spread inside of the panel and damage the rest of the equipment

This type of switchgear is usually not used in cases where high reliability is required. But they are widely used for distribution secondary substations. Their main advantage that they can be designed physically small in dimensions and require only small part of the land area required for equivalent open-air substation.

It is possible to design outdoor metal enclosed substation, in that case the enclosure must fulfill the protection requirements for internal equipment against all negative environmental conditions, otherwise, the substation must be inside of the building (indoor) or it must have low-cost weatherproof housing [1].

Figure 2 – Metal-enclosed switchgear type UNIMIX, by ABB

1.1.3 Metal-clad

This is a variation of metal enclosed switchgear where all components are physically separated by others by means of earthed metal sheets. In this type of solution occurred fault can not spread between several compartments.

It is vitally important that busbars are unaffected by a fault in any particular circuit panel so that adjacent panels can safely remain in service until appropriate repairs can be executed. Typically, separation is applied between cable box and instrument transformers, instrument transformer chambers and circuit-breaker and circuit-breaker and busbars.

Such arrangements allow to achieve higher reliability and higher availability systems than may be achieved with metal-enclosed concepts.

Most primary switchgears are of the metal-clad type. Originally this type of switchgears was designed and used for outdoor application. However, in harsh environmental conditions maintenance cost can be high because of fast deterioration.

Nowadays it is common rule for such type of switchgear to be placed in appropriate weatherproofed housing [1].

Figure 3 – Metal-clad switchgear type UNIGEAR, by ABB

1.1.4 Gas-insulated substations (GIS)

A further form of metal-clad substation is the gas insulated substation. This type is mostly used for transmission voltage levels. In this switchgear concept, sulfur hexafluoride (SF_6) creates the main insulation material between the conductive parts of substation, it is non-toxic, not flammable, does not create explosive mixtures and has high arc-flash extinguishing properties. Due to that fact that dielectric strength of SF_6 is almost 2.5 times higher that dielectric strength of air, the dimensions of substation can very small.

There are two basic concepts of GIS existing:

1) First solution is where each phase is physically placed in metal enclosure;
2) Second solution is where all three phases are placed in one metal enclosure.

The advantage of the first type is that it prevents the occurrence of phase-to-phase faults. The second, however, provides the more economic and more compact solution.

Both types are widely used, where the phase isolated concept is being used mostly for higher voltages and solution with phases in one enclosure is being used for lower transmission or for high distribution voltages, i.e. 132 kV. [1]

Figure 4 – SF6 Gas Insulated Metal Enclosed Switchgear (GIS) – on photo: ABB Gas insulated primary distribution switchgear

1.2 Design Recommendations

Distribution substation design must be a combination of reliability and quality of the power supply, safety, economics, maintainability, simplicity of operation, and functionality.

Design conditions which are must be fulfilled:

1. Interrupting devices must be able to function safely and properly under the most severe duty to which they may be exposed;
2. Accidental contact with energized conductors should be eliminated by means of enclosing the conductors, installing protective barriers, and interlocking;
3. The substation should be designed so that maintenance work on circuits and equipment can be accomplished with these circuits and equipment de-energized and grounded;
4. Warning signs should be installed on electric equipment accessible to both qualified and unqualified personnel, on fences surrounding electric equipment, on access doors to electrical rooms, and on conduits or cables above 600 V in areas that include other equipment;
5. An adequate grounding system must be installed;
6. Emergency lights should be provided where necessary to protect against sudden lighting failure;
7. Operating and maintenance personnel should be provided with complete operating and maintenance instructions, including wiring diagrams, equipment ratings, and protective device settings [2].

A variety of basic circuit arrangements are available for distribution substations. Selection of the best system or combination of systems will depend upon the needs of the power supply process.

In general, system costs increase with system reliability if component quality is equal. Maximum reliability per unit investment can be achieved by using properly applied and well-designed components.

If the substation is designed to supply a manufacturing plant, continuity of service may be critical. Some plants can tolerate interruptions while others require the highest degree of service continuity.

The system should always be designed to isolate faults with a minimum disturbance to the system and should have features to provide the maximum dependability consistent with the plant requirements and justifiable cost.

1.3 Main requirements to the basic scheme arrangements for substations

Main scheme of substation determines not only electrical, but physical arrangement of the primary equipment. During the design of substation several factors must be considered, such as: reliability, economy, extendibility, maintainability, operational flexibility, protection arrangement, short circuit limitations, land area, safety and simplicity dictated by function and importance of the substation.

1) Reliability:

Reliability of power supply one of the most important factors which is must be taken into account in selection of main scheme. Full reliability of supply is possible to achieve by full duplicating all circuits and equipment such that in case of fault or maintenance, all damaged/switched off connection will be available. In real life, it is not possible because it would be extremely expensive, and real areas of open-air substations would be huge. Selected main scheme must be balanced between maximum possible reliability and capital investment.

It is possible to categorize all power consumers in 4 main categories, taking onto account outage time in case of fault occurrence. All main schemes are categorized according to this groups.

Category 1 – No outage necessary within the substation for either maintenance or fault; e.g. the 1 ½ breaker scheme under maintenance conditions in the circuit breaker area;

Category 2 – Short outage necessary to transfer the load to an alternative circuit for maintenance or fault conditions; e.g. the double busbar scheme with bypass disconnect switch and bus-coupler switch under fault or maintenance conditions in the circuit breaker or busbar area;

Category 3 – Loss of a circuit or section; for example, the single busbar with bus section circuit breaker scheme for a fault in the circuit breaker or busbar area. The single feed scheme also comes under category 3 service continuity and for this arrangement the addition of incoming circuit breakers, busbar and transformer circuit breakers does not improve the classification;

Category 4 – Loss of substation; for example, the single busbar scheme without bus sectionalizing for a fault in the busbar area.

2) Extendibility:

The design must allow future extensions of the substation scheme. It should be possible to add new feeders to the substation and care should be taken to minimize outages and duration of outages during construction and commissioning. Where future extension most probably will involve significant changes (for example, change single busbar arrangement to double busbar) then the best solution would be to install the final arrangement at the beginning.

3) Maintainability:

The switching scheme must consider the electricity supply company system planning and operations procedures together with knowledge of reliability and maintenance requirements for the proposed substation equipment. The need for circuit breaker disconnect switch bypass facilities may therefore be obviated by an understanding of the relative short maintenance periods for modern switchgear.

4) Operational flexibility:

The switching scheme must permit the required power flow control of individual circuits and groups of circuits. In a two-transformer substation operation of either or both transformers on one infeed together with the facility to take out of service and restore to service either transformer without loss of supply would be a normal design consideration. In general, a multiple busbar arrangement will provide greater flexibility than a ring busbar.

5) Protection arrangements:

The switching scheme must allow for the protection of each system element by provision of suitable CT locations to ensure overlapping of protection zones. The number of circuit breakers that require to be tripped following a fault, the auto-reclose arrangements, the type of protection and extent and type of mechanical or electrical interlocking must be considered.

For example, a 1½ breaker substation layout produces a good utilization of switchgear per circuit but also involves complex protection and interlocking design which all needs to be engineered and thus increases the capital cost.

6) Short circuit limitations:

In order to keep fault levels down parallel connections (transformers or power sources feeding the substation) should be avoided. Multi-busbar arrangements with sectioning facilities allow the system to be split or connected through a fault limiting reactor. It is also possible to split a system using circuit breakers in a mesh or ring type substation layout although this requires careful planning and operational procedures.

7) Cost:

A satisfactory cost comparison between different substation switching scheme is extremely difficult because of the differences in performance and maintainability. It is preferable to base a decision for a particular scheme on technical grounds and then to determine the most economical means of achieving these technical requirements [2].

1.4 Basic scheme arrangements for substations

1.4.1 Single busbar arrangement

The single bus layout is easy to operate, provides minimal dependence on signaling to ensure satisfactory protection performance, and is flexible enough to allow additional feeders to be connected in the future. Figure 5 shows a diagram of a single bus with fourteen feeder circuits and one bus-coupler circuit breaker.

Figure 5 – Single bus bar scheme arrangement with bus-coupler

Main characteristics [3]:

1) Each feeder is protected by its own circuit breaker and hence a fault on a feeder/transformer does not necessarily result in interruption of power supply to other feeders;
2) A fault on a feeder or transformer circuit breaker causes loss of the transformer and feeders circuits. They may be restored after isolating the faulty circuit breaker;
3) A fault on a bus-coupler circuit breaker causes complete shutdown of the whole substation. All circuits may be restored after isolating the faulty circuit breaker and the substation will be sectionalized under these conditions;

4) A busbar fault causes loss of one transformer and all feeders on that bus section. Maintenance of one busbar section will cause the temporary outage of all circuits. Can be used only where loads can be interrupted;
5) Bus cannot be extended without de-energizing of half of the substation;
6) Difficult to do any maintenance, maintenance of a feeder or transformer circuit breaker involves shutting down of that circuit;
7) Lowest possible cost among all available busbar arrangements in the present;
8) The introduction of bypass disconnectors between the busbar and circuit disconnector (Figure 6) allows to perform maintenance of the circuit breaker without shutting down of the feeder;
9) Bypass facilities may also be obtained by using a disconnector on the out-going feeders between two adjacent switchgear bays (Figure 7). The circuits are paralleled onto one circuit breaker during maintenance of the other. It is possible to maintain protection (although some adjustment to settings may be necessary) during maintenance but if a fault occurs then both circuits are lost. With the high reliability and short maintenance times involved with modern circuit breakers such bypasses are not nowadays so common.

Figure 6 – Single Bus scheme with bypass disconnector

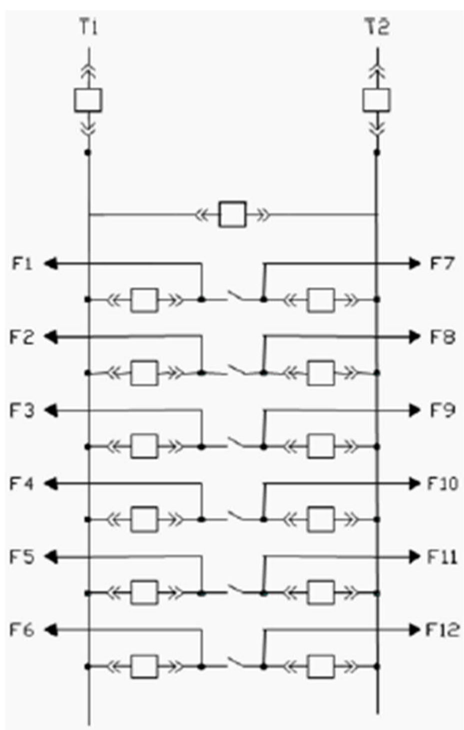

Figure 7 – Single busbar arrangement with bypass disconnector between two adjacent bays

1.4.2 Mesh arrangement

Each section of the mesh scheme, as shown in Figure 8, is included in a line or transformer protection zone so no specific separate busbar protection is required. Operation of two circuit breakers is required to connect or disconnect a circuit and disconnection involves opening the mesh.

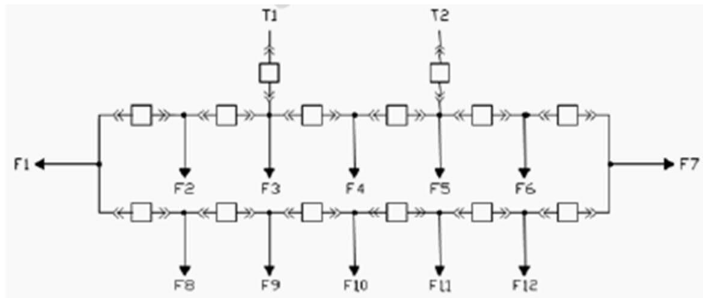

Figure 8 – Mesh Scheme

Line or transformer circuit disconnect switches may then be used to isolate the particular circuit and the mesh reclosed.

Main characteristics [3]:

1. Circuit breakers may be maintained without interruption in power supply or protection and no additional bypass facilities are required. The particular circuit may be fed from an alternative route around the mesh;
2. If a fault occurs during a breaker maintenance period, the mesh can be separated into two sections;
3. Busbar faults will only cause the loss of one circuit;
4. Circuit breaker faults will involve the loss of a maximum of two circuits. Breaker failure during a fault on one of the circuits causes loss of one additional circuit due to operation of breaker-failure relay protection;
5. Maximum security is obtained with equal numbers of alternatively arranged feeding and loading connections;
6. Flexible operation for breaker maintenance. Any breaker can be removed for maintenance without interrupting load;
7. Does not use main bus;
8. Each circuit is fed by two breakers however the ratio of circuit breakers to circuits is 1/1;
9. Automatic reclosing and protective relay circuits is quite complicated;
10. If a single set of relays is used, the circuit must be taken out of service to maintain the relays;
11. Requires potential devices on all circuits since there is no definite potential reference point These devices may be required in all cases for synchronizing, live line, or voltage indication;
12. Low initial and ultimate cost.

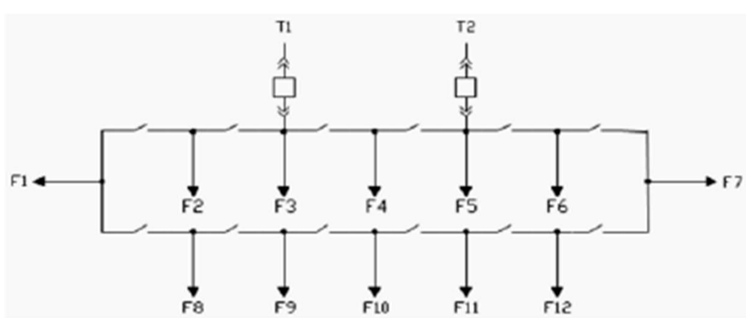

Figure 9 – Ring Bus Scheme

Maintenance on a disconnect switch requires an outage of both adjacent circuits. The inability of disconnectors to break load current is also an operational disadvantage.

1.4.3 Double busbar (transfer bus) arrangement

A typical transfer busbar arrangement is shown in Figure 10.

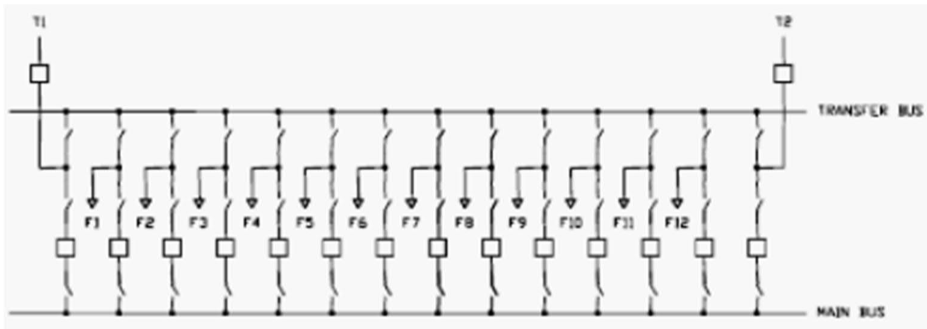

Figure 10 – Transfer Bus Scheme

Main characteristics [3]:

1. This is basically, a single bus scheme with bus section circuit breaker and an extra bus-coupler breaker with bypass disconnector facilities. When circuit breakers are under maintenance the protection is arranged to trip the bus-coupler breaker;
2. Failure of bus or any circuit breaker results in outage of half of the substation;
3. Any circuit breaker can be taken out of service for maintenance;
4. The use of circuit breaker bypass isolator facilities is not considered as a big advantage or benefit since modern circuit breaker maintenance times are short and in highly interconnected systems alternative feeder arrangements are normally possible;
5. This arrangement is considered to offer less flexibility than the double busbar scheme;
6. Potential devices may be used on the main bus for relay protection;
7. Low initial and ultimate cost.

1.4.4 Double busbar (double busbar single breaker) arrangement

The double busbar arrangement has the flexibility to allow the grouping of circuits onto separate busbars with facilities for transfer from one busbar to another for maintenance or operational reasons. A typical double busbar arrangement is shown in Figure 11.

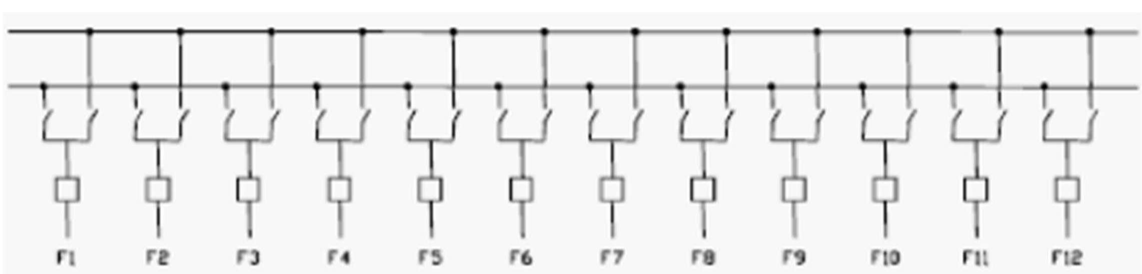

Figure 11 – Double Bus Scheme

Main characteristics [3]:

1. Each circuit may be connected to either busbar using the bus bar selector disconnector. On-load busbar selection can be implemented with using the bus-coupler circuit breaker;
2. Feeder breaker failure takes all circuits connected to that bus section out of service;
3. Bus-coupler circuit breaker failure takes entire substation out of service;

4. Either main bus may be isolated for maintenance;
5. Permits some flexibility with two operating buses;
6. Circuit can be transferred readily from one bus to the other by use of bus-coupler circuit breaker and bus selector disconnector;
7. Busbar and busbar breaker maintenance may be carried out without loss of supply to any circuit;

1.4.5 1 ½ Circuit breaker arrangement.

The arrangement is shown in Figure 12. It offers the circuit breaker bypass facilities and security of the mesh arrangement coupled with some of the flexibility of the double busbar scheme. The layout is used at important high voltage substations and large generating substations where the cost can be offset against high reliability requirements.

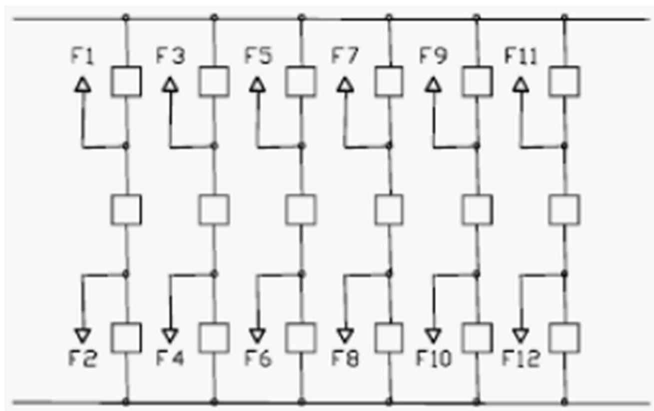

Figure 12 – 1 ½ Breaker Scheme

Essentially the scheme requires 1 ½ circuit breakers per connected transmission line or transformer circuit and hence the name of this configuration.

Main characteristics [3]:

1. High reliability against loss of supply;
2. Bus failure does not cause power loss at any feeder;
3. Breaker failure of bus side breakers does not lead to loss any other circuit from service;
4. Either main bus can be taken out of service at any time for maintenance;
5. Most flexible operation;
6. Simple operation; no disconnect switching required for normal operation;
7. The circuit breakers and other system components must be rated for the sum of the load currents of two circuits;
8. Relaying and automatic reclosing are more complex since the middle breaker must be responsive to either of its associated circuits;
9. Additional costs of circuit breakers are involved together with complex protection arrangements.

2 Basic Theory about Main Equipment

In this chapter, it is necessary to review the main primary equipment used in substations, its types, features and applications. For each type, a basic theory is given that describes the basic principles of operation of devices such as current and voltage measuring transformers, as well as high-voltage circuit breakers of different types. This chapter will also cover the main issues and definitions related to relay protection, which should be taken into account when designing substations.

2.1 Instrument transformers.

Instrument transformers (ITs) are transformers designed to supply measuring instruments, meters, relays and other similar devices. There are two types of instrument transformer.

Current transformers, in which the secondary current is under normal working conditions, practically proportional to the primary current and phase shifted from it by an angle close to zero in the appropriate direction for connections; and

Voltage transformers, in which the secondary voltage is under normal working conditions, practically proportional to the primary voltage and phase shifted from it by an angle close to zero in the appropriate direction for connections.

The purpose of instrument transformers is to reduce the voltage and current of an electrical network to a standardized non-hazardous level. They prevent any direct connection between instruments and high voltage circuits which would be dangerous to operators and would need instrument panels with special insulation. They also do away with the need for expensive special instruments when high currents have to be measured. Figure 13 shows a simple circuit diagram in which it can be clearly seen how current transformers (CT) and voltage transformers (VT) are connected to the network [4]. Where the R is for burden and W is for wattmeter.

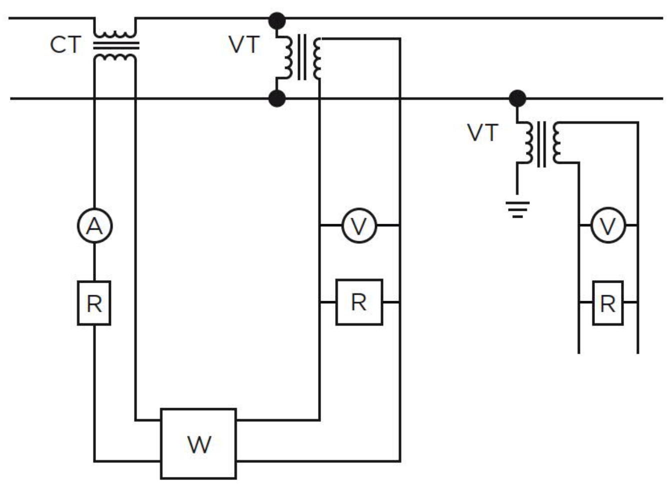

Figure 13 – Example of connections of CT and VTs to the network

2.1.1 Current transformers

The basic principle of the current transformer is the same as that of the power transformer. Like the power transformer, the current transformer also contains a primary and a secondary winding. Whenever an alternating current flow through the primary winding, alternating magnetic flux is produced, which then induces alternating current in the secondary winding. In the case of current transformers, the load impedance or “burden” is very small. Therefore, the current transformer operates under short circuit conditions. Also, the current in the secondary winding does not depend on load impedance but instead depends on the current flowing in the primary winding.

The current transformer basically consists of an iron core upon which primary and secondary windings are wound. The primary winding of the transformer is connected in series with the load and carries the actual current flowing to the load, while the secondary winding is connected to a measuring device or a relay. The number of secondary turns is proportional to the current flowing through the primary; i.e., the larger the magnitude of current flowing through the primary, more the number of secondary turns.

The ratio of primary current to the secondary current is known as the current transformation ratio of the CT. Usually the current transformation ratio of the CT is high. Normally the secondary ratings are of the order 5 A, 1 A, 0.1 A, whereas the primary ratings vary from 10 A to 3000 A or more.

The CT handles much less power. Rated burden can be defined as the product of current and voltage at the secondary side of the CT. It is measured in VA.

The secondary of a current transformer should not be disconnected from its rated burden while current is flowing in the primary. As the primary current is independent of the secondary current, the entire primary current acts as a magnetizing current when secondary is opened. This results in deep saturation of the core, which cannot return to normal state and so the CT is no longer usable.

Based on the function performed by the current transformer, it can be classified as follows:

1) **Measuring current transformers.** These current transformers are used along with the measuring devices for the measurement of current, energy, and power.
2) **Protective current transformers.** These current transformers are used along with the protection equipment such as trip coils, relays, etc.

Based on the function construction, it can also be classified as follows:

1) **Bar Type.** This type consists of a bar of suitable size and material forming an integral part of the transformer.
2) **Wound Type.** This type has a primary winding of more than one full turn wound over the core.
3) **Window Type.** This type has no primary winding. The secondary wind of the CT is placed around the current flowing conductor. The magnetic electric field created by current flowing through the conductor induces current in the secondary winding, which is used for measurement [5].

In the theory of current transformers there are defines two types of errors: current and phase. The current error εi is the error which the transformer introduces into current measurements. It stems from the fact that its transformation ratio is not exactly as rated current error εi expressed as a percentage. The phase shift or phase error of a current transformer, δi, is the phase difference between the vectors of the primary and secondary currents, with vector directions being chosen so that the angle is zero for a perfect transformer. In practice, for loads with $\cos \beta = 0{,}8$, phase shift is not a limiting factor, so transformers are calculated for the maximum ratio error, i.e. when Is and Io are in phase [4].

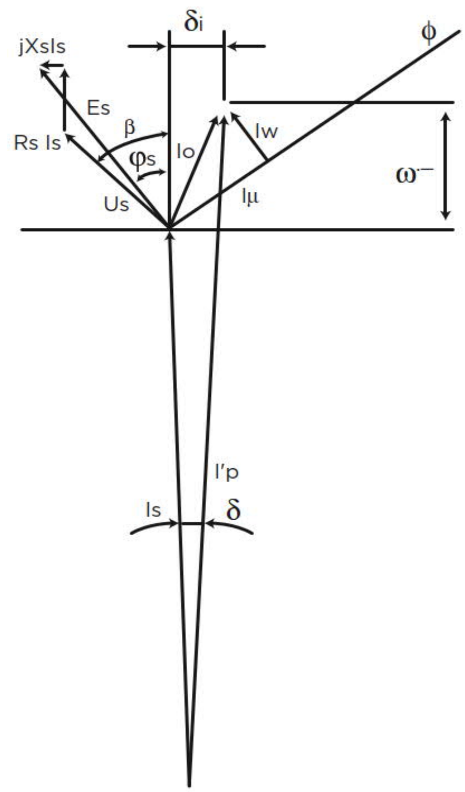

Figure 14 – Phasor diagram of current transformer

Accuracy class. Accuracy class tells you how accurate the current transformer is. Accuracy class shall be 0.2, 0.5, 1, 3 or 5. For example, if the accuracy class of a current transformer is 1, then the ratio error will be ±1% at the rated primary value.

Rated secondary current. The value of rated secondary current shall be 5 A. The secondary currents rating of 2 and 1 A may also be used in some cases.

Rated burden. The product of current and voltage at the secondary side of the CT is called the rated burden. It is measured in *VA*.[5]

To ensure that designed switchgear will runs properly, during choosing procedure of CTs must be taken into account several points [4]:

1) Type of installation. Indoor or outdoor. Depends on that it is possible to predefine the type of CT;
2) Voltage level of installation. Voltage refers to insulation level which must be defined;
3) Calculation of required ratio of current transformer;
4) Accuracy class depending on the purpose of used CT. Either it is meant to be used for measuring or/and for protection;
5) Rated burden of CT;
6) Rated precision limit factor (protection transformers);
7) Due to that fact that current transformers connected to the network in series, in case of fault occurrence they can be affected by the fault current. That means that they must be checked for thermal and electrodynamic withstand during choosing procedure;
8) Rated frequency;
9) Number of secondary cores;
10) Construction details.

2.1.2 Voltage transformers

The primary of a voltage transformer is connected to the terminals between which the voltage is to be measured, and the secondary is connected to the voltage circuits of one or more measuring devices, connected in parallel. Voltage transformers are more like power transformers than current transformers are. For reasons of construction and insulation, VTs are normally made with a rectangular core and the secondaries (if there is more than one) are wound on the same core. Unlike CTs, they are therefore not independent, and the load of one secondary influences the accuracy of the other. VTs may be used to measure the voltage between phases or between a phase and earth. In this case one end of its primary winding will be directly earthed, inside or outside the transformer.

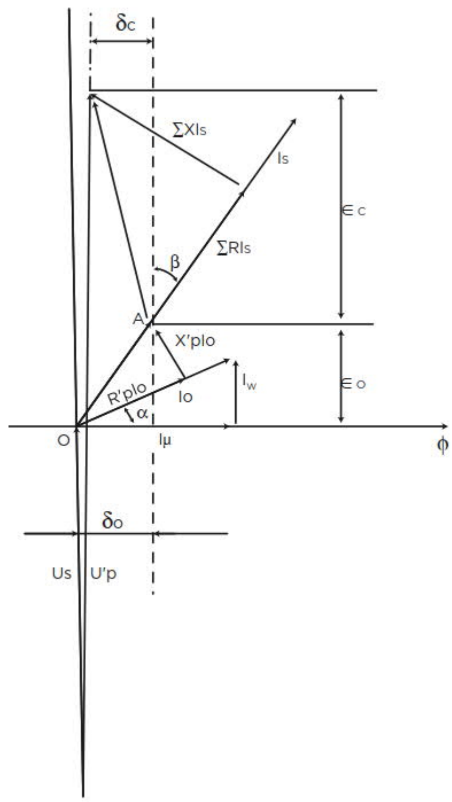

Figure 15 – Phasor diagram of voltage transformers

A voltage error is an error introduced by the transformer in a voltage measurement, resulting from its transformation ratio not being exactly as the rated one, the voltage error ε_u is expressed as a percentage. The phase error of a voltage transformer ε_u is the phase difference between the vectors of the primary and secondary voltage. Both, the ratio error and the phase error are made up of the unloaded error plus the load error, as shown in fig. 15. The operating margin of the transformer in UNE, IEC and other standards is between 0.8 and 1.21 U_{pn}.

The basic definitions formed above for CTs mostly are valid for VTs.

Basic procedure for choosing the VT:

1) Type of service: indoor or outdoor. Altitude is also a factor to be considered, when it is higher than 1.000 m above sea level;
2) Insulation level;
3) Rated transformation ratio;
4) Precision class;
5) Power;

6) Voltage factor;
7) Rated frequency;
8) Number of secondaries;
9) Construction details.

2.2 Circuit Breakers

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by excess current from an overload or short circuit. Its basic function is to interrupt current flow after a fault is detected. Unlike a fuse, which operates once and then must be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation.

Circuit breaker essentially consists of fixed and moving contacts. These contacts are touching each other and carrying the current under normal conditions when the circuit is closed. When the circuit breaker is closed, the current carrying contacts, called the electrodes, engaged each other under the pressure of a spring.

During the normal operating condition, the arms of the circuit breaker can be opened or closed for a switching and maintenance of the system. To open the circuit breaker, only a pressure is required to be applied to a trigger.

Whenever a fault occurs on any part of the system, the trip coil of the breaker gets energized and the moving contacts are getting apart from each other by some mechanism, thus opening the circuit.

Nowadays, there are 4 the most common types of circuit breakers which are used the most. Basic description of each type will be given below [6].

2.2.1 Air circuit breakers

An air circuit breaker employs air as the interrupting insulation medium. Of all the insulating media mentioned, air is the most easily ionized and, hence, arcs formed in air tend to be serve and persistent. The switching elements for an air current, breaker, consists of main and auxiliary contacts. The auxiliary contacts open before the main contacts do, and the arc is drawn on them, thereby avoiding serve pitting of the main contacts [6].

2.2.2 Oil Circuit Breakers

Oil circuit breakers have their contacts immersed in insulating oil. They are used to open and close high-voltage circuits carrying relatively large currents in situations where air circuit breakers would be impractical because of the danger of the exposed arcs that might be formed. When the contacts are drawn apart, the oil covering them tends to quench the arc by its cooling effect and by the gases thereby generated, which tend to "blow out" the arc. At the instant the contacts part, the arc formed at each contact not only displaces the oil but decomposes it, creating gas and a carbon residue. If these carbon particles were to remain in place, as a conductor they would tend to sustain the arc formed. However, the violence of the gas and the resulting turbulence of the oil disperse these particles and they eventually settle to the bottom of the tank. The insulating oil normally used as a dielectric strength of around 30 kV per one tenth of an inch (compared to a similar value of 1 kV for air). Oil is also an effective cooling medium [6].

2.2.3 Vacuum Circuit Breaker

Here the contacts are drawn apart in a chamber from which air has been evacuated. The electric arc is essentially an electric conductor made up of ionized air. Thus, if there is no air, theoretically the arc cannot form. In practice, however, a perfect vacuum is not likely to be obtained. The small residual amount of air that may exist permits only a small arc to be formed and one of only a very short duration.

The same vacuum, however, will not dissipate the heat generated as readily as other insulating media. This type of breaker has certain advantages in terms of its size and simplicity.[6]

2.2.4 Sulphur hexafluoride (SF6) breaker

This type of breaker is similar to the vacuum types of breaker except that the vacuum is replaced by an inert non-toxic, odorless gas-sulphur hexafluoride (SF_6). This gas extinguished the arc so rapidly as almost to prevent its formation. It is also excellent heat-dissipating characteristics, and its dielectric strength is very much greater than that of oil.

The breakers are constructed to modules capable of operation at voltages from 34.4 kV at gas pressure of 45 psi to 362 kV at 240 psi. By connecting two or three such modules in series, breaker capable of operating at 800 kV at 240 psi can be constructed with two-three-cycle interrupting time.[6].

2.3 Basic definitions about protection

One of the main parts in the design of any switchgear is the correct selection and adjustment of the protection system. The protection system should be designed in such a way that it meets the modern requirements of safety, as well as is cost-effective. Cost effectiveness has always been challenging for power system protection - also known as protection relaying - due to the importance of safety; both safety of persons that could be exposed to power system failures, as well as the safety of equipment. [7]

2.3.1 Intelligent Electronic Device (IED)

Microprocessor-based voltage regulators, protection relays, circuit breaker controllers, etc. with the capability of communication with other devices are Intelligent Electronic Device (IEDs). This paragraph contains a brief explanation of the basic definition of IED electrical interfacing, functionality, HMI and setting studies.

1) **Electrical interfacing:** The figure below shows all possible electrical interfacing of an Intelligent Electronic Device (IED);

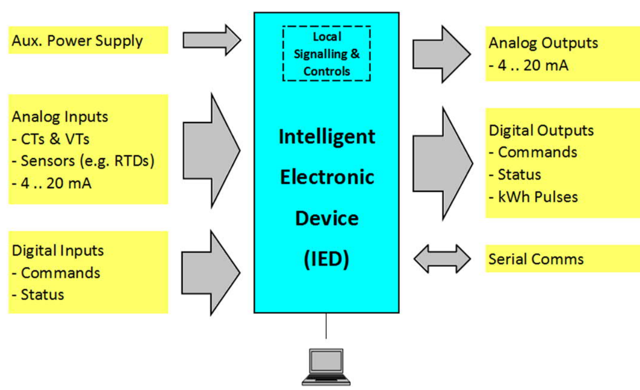

Figure 16 – Electrical interfacing of an IED

2) **Auxiliary power supply**: Older protection relays and voltage regulators may not need auxiliary supply, but IEDs always require an auxiliary power supply. Most modern IEDs works with an extended range, e.g. 24 – 250 V DC /110 – 240 V AC;
3) **Analog inputs**: Protection relays and voltage regulators are always provided with current and voltage transformer inputs. Besides that, devices may be provided with sensor inputs (e.g. temperature sensors) and/or 4..20 mA inputs. It is important to take into account that for some IEDs rated secondary current (1 A or 5 A) and frequency (50 or 60 Hz) must be specified before ordering, also it is important that the correct phase of the sensing voltages and currents, and the right direction of the currents are considered;

4) **Digital inputs**: Some IEDs require potential-free contacts for digital (logic) inputs, while others recognize the positive power supply voltage (source) or negative power supply voltage (sink) as a logical 1. Digital inputs may be commands or as status information;
5) **Analog outputs**: Some IEDs are provided with transducer outputs, e.g. 4..20 mA or 0..10 V. Mostly these outputs are programmable. These outputs can be active type or passive type outputs. The passive type requires external power supply;
6) **Digital outputs**: Digital outputs can be potential free normally open, normally close or change-over contacts or solid-state contacts. It is important to check switching capability of the output contacts, because differences can be significant. Digital outputs may be commands or status information;
7) **Communication ports**: There are several ports possible for communication like RS 485, ethernet (RJ45), optical, etc. IEDs are mostly also provided with an RS 232 or USB port for local communication with a laptop or PC;
8) **Functionality**: The extended functionality of an IED can be separated into the following groups: protection, control, monitoring, metering and communication;
9) **Protection:** This functionality covers all protection functions to protect a generator, motor, transformer or feeder;
10) **Control functions and logics:** These elements may be control loops in voltage regulators, control logics in circuit breakers, etc.;
11) **Monitoring:** Each IED should have internal self-supervision and aux. supply monitoring. A “watch-dog” or “healthy” output contact will close if the IED is operating well. Monitoring may also include loss of analog sensing inputs (e.g. loss of voltage, current, temperature sensors), trip circuit supervision, event recording, etc.;
12) **Metering:** Most IEDs contain metering values including line voltages (V), phase currents (A) and voltages (V), neutral current (A), residual voltage (V), frequency (Hz), power (MW, MVAr, MVA) and energy (kWh, kVArh), harmonics, disturbance recording, temperature and analog channels. Some IEDs are also provided with programmable transducer outputs;
13) **Serial communication:** IEDs could support protocols like Modbus RTU/ASCII, DNP3(serial), IEC60870-5-103, etc. In order to enable interoperation of IEDs from different vendors, IEC created the modern IEC 61850 standard;
14) **Human Machine Interfacing (HMI)**: Almost all IEDs are equipped with Human-Machine Interface (HMI) software for commissioning and fault diagnosis. Besides that, most IEDs are also provided with a keypad and a display, or it is optional available;
15) **Setting Studies**: In the past a commissioning engineer could adjust a relay or a voltage regulator with three screws and a few dip switches or jumpers, but an IED may contain over 1,000 settings. Excellent HMI software could help to overview all settings and keep them under control. But even then, a setting study by a specialist is mostly necessary. Besides that, the IED should be tested thoroughly with these settings [8].

2.3.2 IEC 61850 description

The IEC 61850 protocol standard for substation enables the integration of all protection, control, measurement and monitoring functions by one common protocol. It provides the means of high-speed substation applications, station wide interlocking and other functions which needs intercommunication between IEDs. The well described data modelling, the specified communication services for the most recent tasks in a station makes the standard to a key element in modern substation systems.

The data modelling uses the concept of logical nodes to identify the published information for communication. The standard defines a set of logical nodes, each representing a communication view of a process function with a number of data objects. The standard cannot cover all possible information that is given, for example, by a protection function of vendor A or vendor B or for the variants of a protection function given by the process part which is protected. For example, a transformer differential - or line differential protection, because the standard defines only a differential protection. Therefore, it is possible to adapt the logical node, which is defined in the standard, as a logical node class. The standard defines methods to describe the actual used logical node as a logical node type which is then based upon the logical node class. This allows all partners to interpret the logical node type information because the description is completely given in the standard. The type description of all logical nodes is part of the Data Type Template (DTT) section in the SCL description file of a station or the IED [9].

2.3.3 GOOSE protocol

IEC 61850 (IEC 61850 – Communication Networks and Systems in Substations) standard defines GOOSE protocol (Generic Object-Oriented Substation Event) as a publisher/subscriber type communication. This protocol is used for information exchange between IEDs in a Substation over the Ethernet.

IEC 61850 defines a special XML based language used for describing a substation and substation elements called SCL (Substation Configuration Language). Different levels of substations can be described using this language, so different files can exist, such as:

- ICD (IED Capability Description) – it defines the complete capability of IED;
- SSD (System Specification Description) – it contains complete specification of a substation automation system, including single line diagram for the substation and its functionalities (logical nodes);
- SCD (Substation Configuration Description) – it describes complete substation details. It contains substation, communication, IED and Data type template sections.

GOOSE protocol is an event-based protocol. The concept of GOOSE communication is that the publisher periodically sends messages and when an event happens (ex. Trip, Contactor closed …), it sends a burst of messages with new data. Because the protocol is publisher/subscriber based, there is no confirmation that the sent message is correctly received by the subscriber, so the message burst minimalizes the chance of message loss.

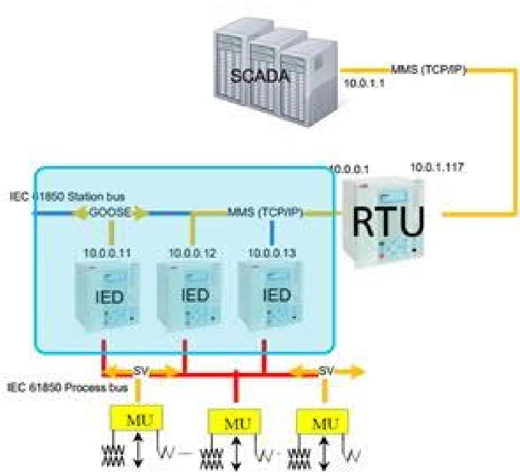

Figure 17 - GOOSE communication inside the Substation

All messages are published under a topic. The subscriber receives all messages from the system, but filters and parses only the messages sent within the subscribed topic [10].

2.3.4 MODBUS protocol

Modbus is a serial communications protocol originally published by Modicon (now Schneider Electric) in 1979 for use with its programmable logic controllers (PLCs). Modbus has become a de facto standard communication protocol and is now a commonly available means of connecting industrial electronic devices. Modbus is popular in industrial environments because it is openly published and royalty-free. It was developed for industrial applications, is relatively easy to deploy and maintain compared to other standards and places few restrictions other than the size on the format of the data to be transmitted. The Modbus uses the RS485 as its physical layer.

Modbus enables communication among many devices connected to the same network, for example, a system that measures temperature and humidity and communicates the results to a computer. Modbus is often used to connect a supervisory computer with a remote terminal unit (RTU) in supervisory control and data acquisition (SCADA) systems. Many of the data types are named from industry usage of Ladder logic and its use in driving relays: a single-bit physical output is called a coil, and a single-bit physical input is called a discrete input or a contact [11].

2.3.5 SCADA

Supervisory control and data acquisition (SCADA) is a system of software and hardware elements that allows industrial organizations to:

- Control industrial processes locally or at remote locations
- Monitor, gather, and process real-time data
- Directly interact with devices such as sensors, valves, pumps, motors, and more through human-machine interface (HMI) software
- Record events into a log file

SCADA systems are crucial for industrial organizations since they help to maintain efficiency, process data for smarter decisions, and communicate system issues to help mitigate downtime.

The basic SCADA architecture begins with PLCs or RTUs. PLCs and RTUs are microcomputers that communicate with an array of objects such as factory machines, HMIs, sensors, and end devices, and then route the information from those objects to computers with SCADA software. The SCADA software processes, distributes, and displays the data, helping operators and other employees analyze the data and make important decisions.

For example, the SCADA system quickly notifies an operator that a batch of product is showing a high incidence of errors. The operator pauses the operation and views the SCADA system data via an HMI to determine the cause of the issue. The operator reviews the data and discovers that a circuit breaker was malfunctioning. The SCADA system’s ability to notify the operator of an issue helps him to resolve it and prevent further loss of product [12].

3 Technical Specification for the Design and Determination of the Initial Parameters of the Substation

3.1 Technical specification form University

According to the technical specification received from the University, it is necessary to create a detailed and functioning design of the substation, which should serve for the purposes of science and education as a laboratory installation. The initial conditions indicated that an open type of substation using a double bus system was preferable. In the future, it is also planned to use a 6 kV metal-clad cubicle, so the design process must consider the future possibility of connecting the cubicle.

From the initial conditions, it was known that the expected operating current flowing through the substation's bus bars should not exceed 1 A, since this substation will not serve to transfer real power to the consumer.

This substation must be designed in such a way that it is possible to adjust and select several voltage levels, namely: 0 kV, 6 kV, 22 kV and 35 kV. For this concept, the key element is an autotransformer and a medium-voltage step-up transformer, both of these elements were already purchased at the time of creating the technical specification. The purchased equipment also includes three 35 kV voltage measuring transformers and 1 IED REU615 of the Relion series manufactured by ABB.

Based on all the above input data, the project execution team started working, which included the following stages:

- creating a primary concept and single-line diagram;
- creating the layout of equipment in the proposed construction zone;
- creation of 3D models and mechanical calculations for metal structures that will be used for fixing primary equipment;
- the creation of the interlocking concept;
- creating a detailed design of the control system for the substation, namely the control and protection cabinet;
- preparation of accompanying documentation.

This work contains a basic description of all the stages, but the key place in it is occupied by the design of the control cabinet and the solution of related issues.

3.2 Basic description of the operational modes

3.2.1 0 kV mode

In this operational mode switchgear must be completely deenergized. Moreover, it is not possible to proceed any operations with primary equipment of designed switchgear. This mode serves for safe maintenance and measurement preparations in switchgear.

3.2.2 6 kV mode (operation of ZS1 cubicle)

In this mode of operation, all primary equipment can be energized. At the same time, the main element of the substation at this voltage level is the ZS1 cubicle, on which it is possible to perform some expert measurements, as well as tests for different modes of operation of the metal-clad switchgear. ZS1 will be equipped with the IED REM series, which means that when the motor will be connected to the output terminals of the medium voltage cubicle, it is possible to carry out tests aimed at studying the operating modes of the motor, as well as demonstrating the possibilities of relay protection of motors using REM. Protection and control relays of the REM series is a dedicated motor management relays for the protection, control, measurement and supervision of medium- and large-sized asynchronous and synchronous motors in the manufacturing and process industry.

Benefits and features of the REM series relays [13]:

- Extensive protection and control functionality, either with sensors or conventional instrument transformers;
- Functional scalability and extensive possibilities to easily tailor configurations to application-specific requirements;
- Withdrawable plug-in unit design for swift installation and testing;
- Large graphical display showing customizable SLDs, accessible either locally or through an easy-to-use web-browser-based HMI;
- Extensive life-cycle services;
- Extensive motor protection for medium- and large-sized asynchronous and synchronous motors requiring differential protection;
- Motor protection both during motor start-up and normal run, with protection and fault clearance in abnormal situations as well;
- Additionally, extensive motor supervision capabilities via RTD and mA measurements and optionally arc protection;
- Supports native IEC 61850 Editions 1 and 2, including redundancy HSR and PRP, GOOSE messaging and IEC 61850-9-2 LE for less wiring and supervised communication;
- Supports Modbus, DNP3 and IEC 60870-5-103 communication protocols and different time synchronization methods, including high-accuracy time synchronization via IEEE 1588 V2 Precision Time Protocol.

3.2.3 22 kV mode.

In this mode of operation, all primary equipment of the substation, except the ZS1 cubicle, can be energized. The main purpose of this mode is to perform routine switching operations. Due to that fact that the chosen type of switchgear is open-air, all operations with the equipment will be visible and understandable.

3.2.4 35 kV mode.

The main purpose of this mode is to perform HV insulation test on outputs of HV transformer. The aim of this tests is to study the behavior of different insulation materials which are commonly used in cable manufacturing. Besides that, it is possible to simulate a ground fault cases in this operational mode it is also quite important topic in terms of studying of electrical power engineering.

3.3 Choosing of the type of the substation

The first step in the design of switchgear is to choose the type that will be used in future installation. There are several parameters that shall be considered:

1) Purpose and main function of substation.
   In this case, we are talking about switchgear that will perform the functions of a laboratory unit. That means that installation must be designed in such a way that it is safe to operate, all proceeded actions must be clearly visible and equipment must be accessible as it is possible.
2) Place of installation.
   The designed switchgear is intended for installation inside the building. That means, that requirement that it must be weatherproof is met and it will be protected against water, wind, ice and snow.

The actual area that is possible to use for placement of the substation inside the building is relatively small that means that it must be considered during the procedure of design.

3) Loading level.

According to initial technical specification of designed switchgear there will be no real load through the busbars and all equipment.

Based on the theory described above, for designed switchgear was chosen open-air type of construction in combination with metal enclosed cubicle. Such a mixed type of substation can allow for a greater number of different measurements, which is an advantage for the designed switchgear. Ability to study the operating modes of the open-switchgear type and metal-clad type.

3.4 Choosing of the bus bar arrangement.

Based on the theory discussed above, it was decided to use a double bus bar system , since this configuration is relatively cheap, has the ability to reserve a feeder in comparison with a single bus bar system, and is flexible enough to change the configuration of the substation as needed. Due to the fact that the main task of the designed switchgear is to use it as a laboratory installation, the visual visibility and simplicity of the double bus bar system is an important advantage in choosing the arrangement of the busbars. One of the advantages of a double bus bar system is also an opportunity to study the switching of feeders between the two bus bar systems, thus it is possible to work out the sequence of actions during routine switching at real substations.

However, in conditions of limited space, it can be quite cumbersome, which can complicate the further layout of the main equipment within the substation. Therefore, special attention should be paid to the proper distribution of space within the intended installation site.

3.5 Creation and description of the single-line diagram (SLD)

The figure below shows the SLD of the substation, which shows that it consists of three main connections:

The incoming feeder through which the substation will be powered. It consists of a main circuit breaker (MCB) for 400 V, through which the substation is fed from the external network, an autotransformer 0-0.4 kV, thanks to which it is possible to adjust the voltage at the low voltage terminals of the power transformer 0.4/35 kV, which is also part of the incoming feeder. It also includes a disconnector with earthing switch for 35 kV, a 24 kV circuit breaker and two 24 kV disconnectors for connection to the busbar system.

The first outgoing connection will consist mainly of two 24 kV disconnectors and a MV circuit breaker designed for 24 kV as well.

The second outgoing connection will consist of a ZS1 cubicle (UniGear series from ABB). It is assumed that the cubicle will be equipped with all necessary primary and auxiliary equipment, the voltage level of the cubicle will be 6 kV, the connection to the busbars of the substation will be done through additional 24 kV disconnector, the decision was made for safety purposes, as by direct connection of the cubicle to the busbars 24 kV as a result of erroneous actions may cause serious damage to the equipment.

Each feeder and the busbar system will be equipped with current and voltage measuring transformers.

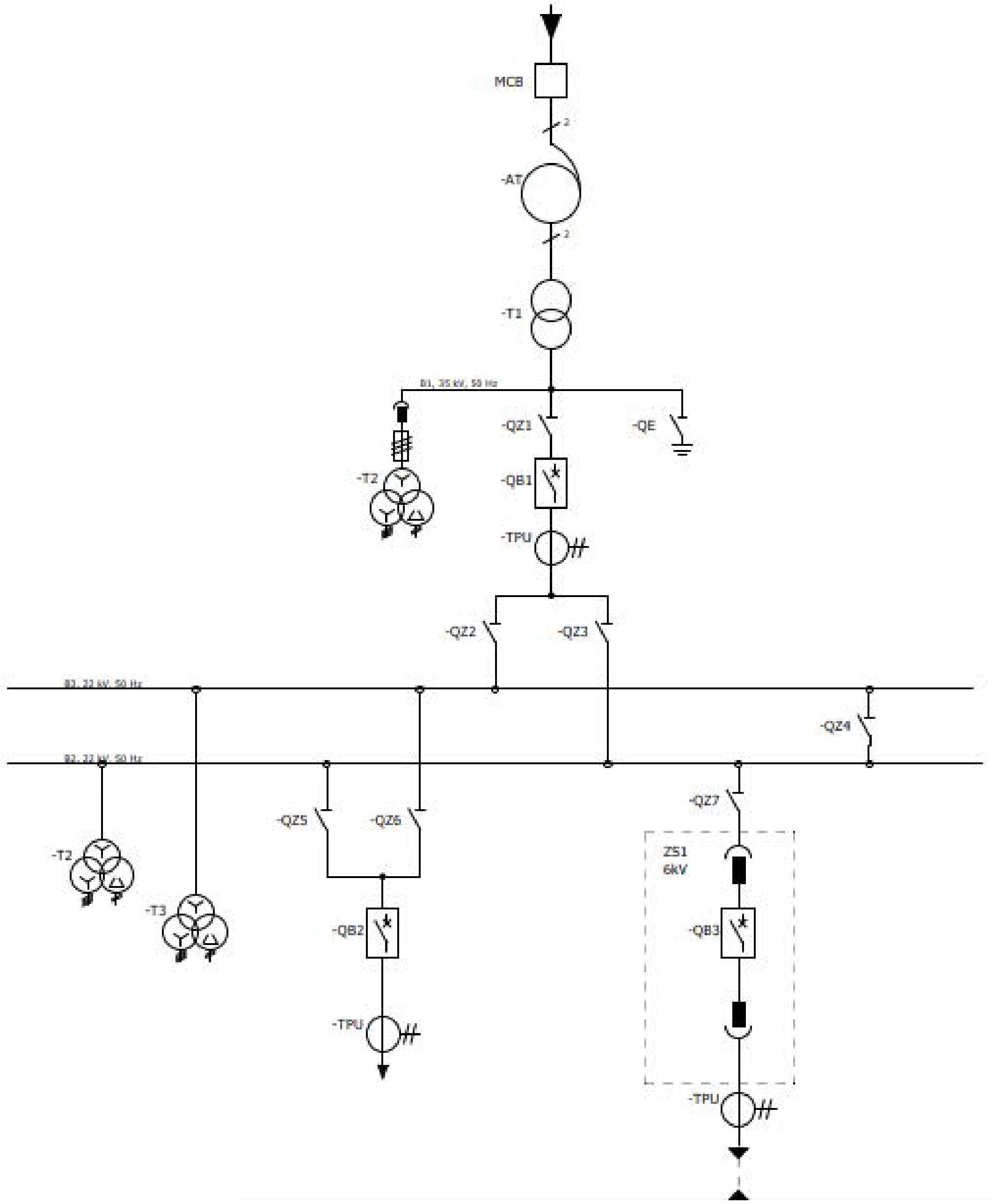

Figure 18 – Single line diagram of designed switchgear

<u>3.6 Creation of the basic layout and 3D model.</u>

The further step in the design was to create a basic layout of the substation in order to see whether the selected configuration can be placed in this space or not. The installation site is approximately 4.4 meters long and 1.5 meters wide, but it is worth noting that the building where the substation is supposed to be installed has relatively high ceilings (more than 6 meters high), which is a great advantage, since in this case it is possible to place the equipment mainly in a vertical plane without critical restrictions. Based on these assumptions, a preliminary layout of the substation was made using the maximum dimensions for the equipment at the appropriate voltage level. This allowed us to evaluate the possibility of placing equipment in a given location without having specific models of primary equipment.

The main difficulty in compiling the layout of the substation was that in conditions of limited space it was quite problematic to comply with the minimum distance between conductors. Based on the standard “IEC 61936-1 Power installations exceeding 1 kV A.C. – Part 1: Common rules” from the table 1 it can be seen that the minimum distance between phases for a voltage level of 36 kV is 320 mm. In the conditions of this substation, it is extremely difficult to comply with this requirement for uninsulated conductors due to the critically small area allocated for design, so it was decided for the first approach to use heat-shrink insulation for medium voltage buses in order to compensate for the lack of dielectric strength between the conductors.

Voltage range	Highest voltage for installation	Rated short-duration power-frequency withstand voltage	Rated lightning impulse withstand voltage [a]	Minimum phase-to-earth and phase-to-phase clearance N	
	U_m r.m.s.	U_d r.m.s.	U_p 1,2/50 µs (peak value)	Indoor installations	Outdoor installations
	kV	kV	kV	mm	mm
	3,6	10	20	60	120
			40	60	120
	7,2	20	40	60	120
			60	90	120
	12	28	60	90	150
			75	120	150
			95	160	160
	17,5	38	75	120	160
			95	160	160
	24	50	95	160	
			125	220	
			145	270	
	36	70	145	270	
			170	320	

Table 1 - Minimum clearances in air – Voltage range I (1 kV < Um ≤ 245 kV) [14]

Subsequently, on the basis of the preliminary layout of the substation project was completed 3D design on the basis of which managed to ensure that the selected equipment may be placed in a given space, as the project was carried out metal where you want to place an extensive part of the main electrical equipment. In the process of creating a 3D model, various variants of equipment layout were considered, which would allow placing it with the most efficient use of space. Thus, based on the compiled model, it was concluded that at this size of the room, it is possible to arrange the equipment in such a way that the minimum distances between the conductors are preserved, which would satisfy the IEC 61936-1 standard. As a result, it was decided to abandon the use of shrink insulation on busbars because it is not necessary.

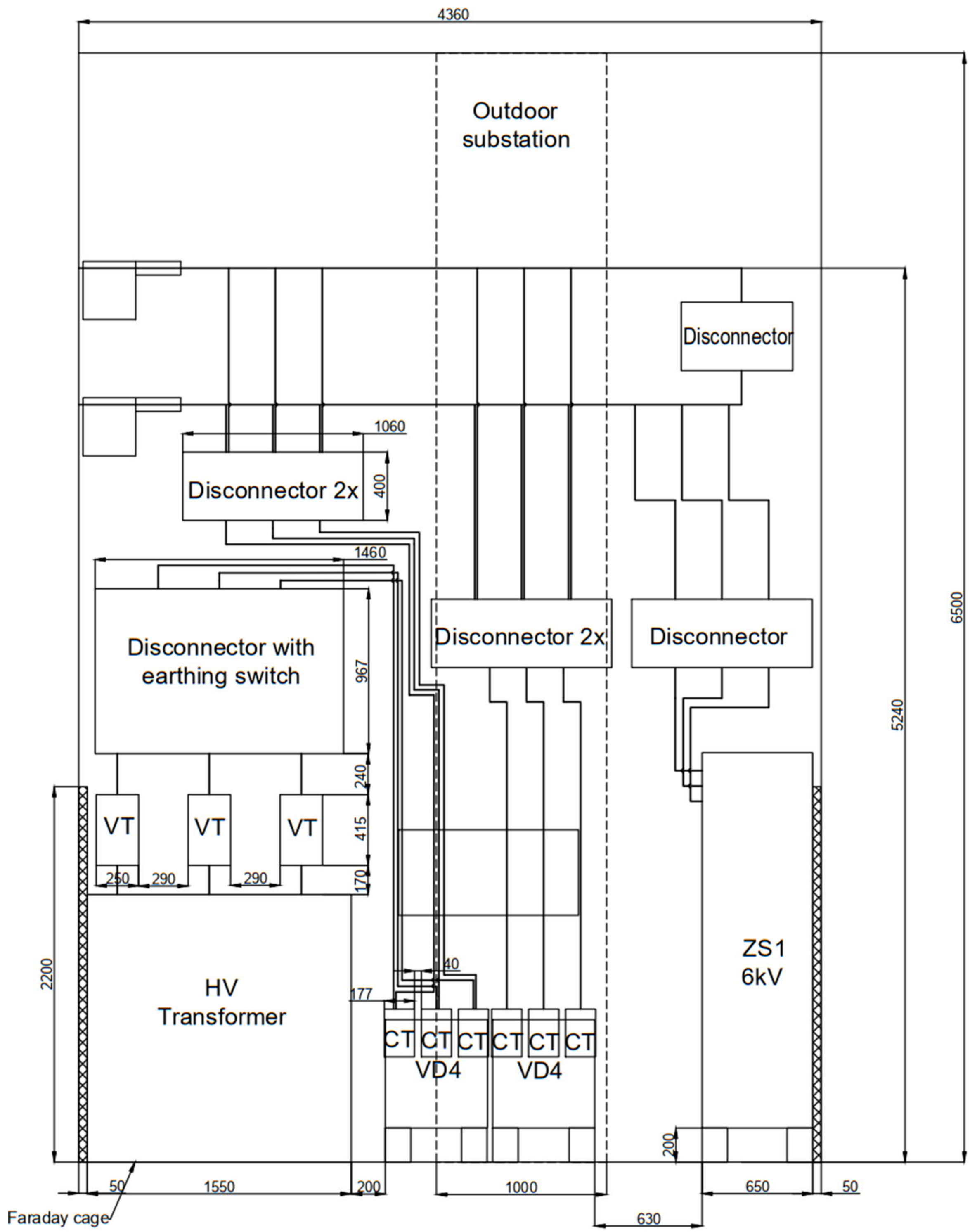

Figure 19 – Basic layout concept of designed switchgear (Front view)

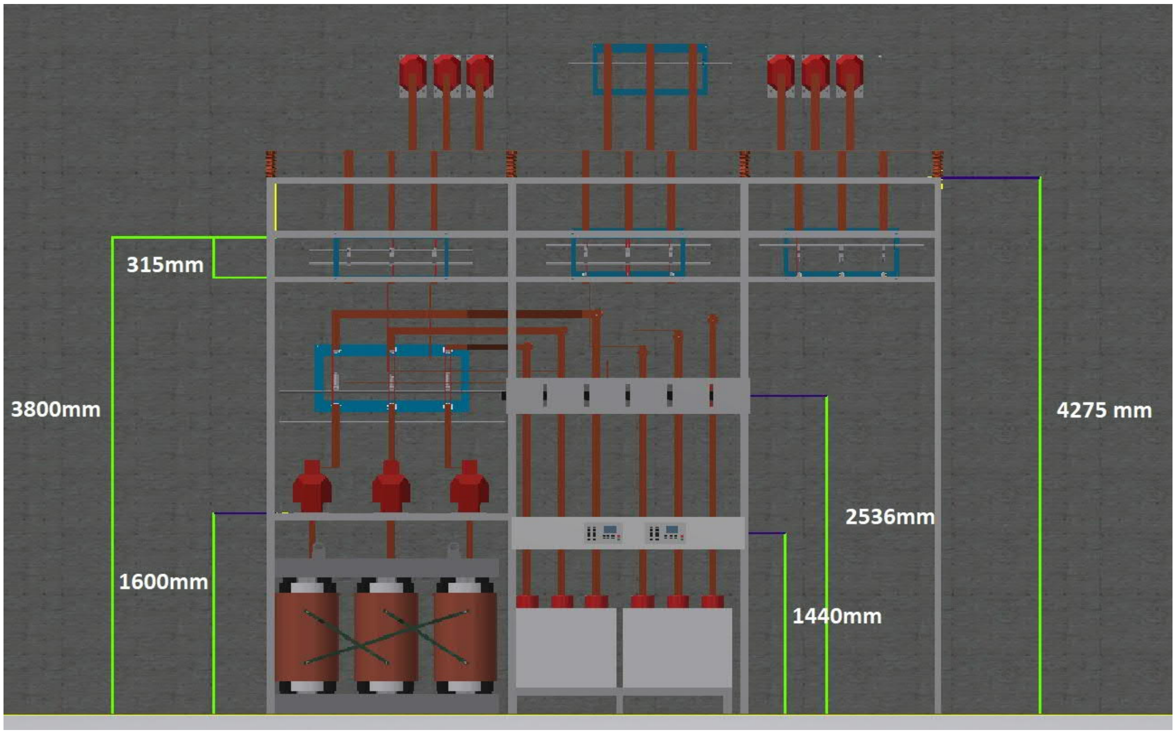

Figure 20 – 3D model of the substation (front view)

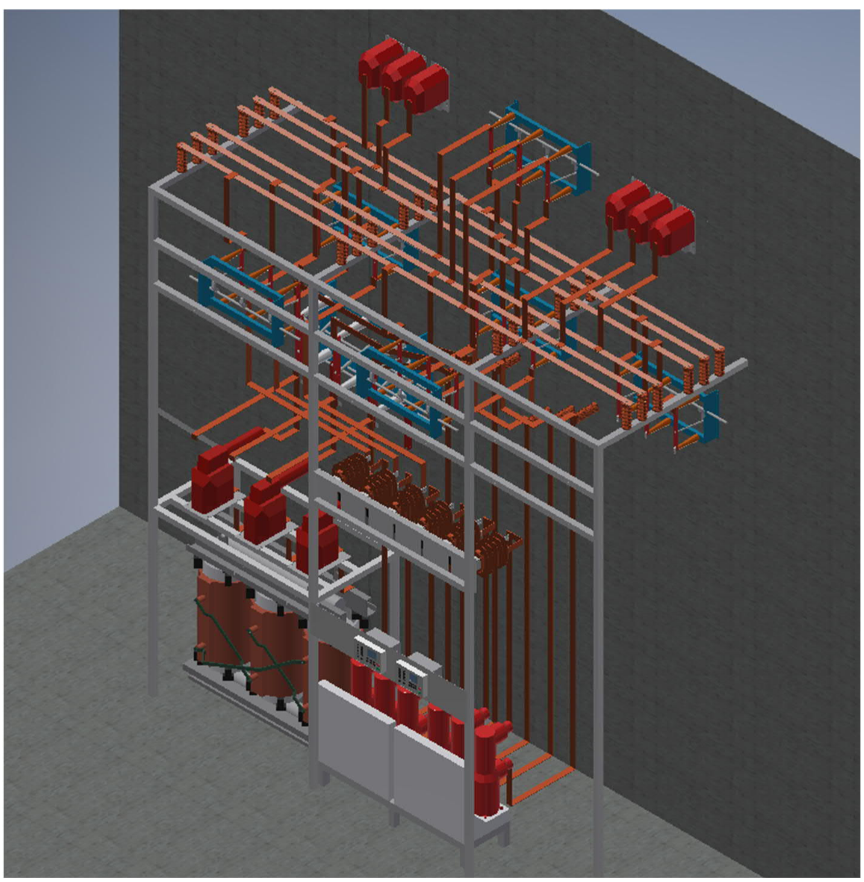

Figure 21 – 3D model of the substation (angle view)

4 Short-Circuit Calculation

As mentioned above, the estimated nominal current flowing through the substation bus bars is estimated at less than 1 A, however, for additional justification and verification of the selected electrical equipment, it is necessary to calculate the short-circuit currents. In addition, the data obtained in this calculation is necessary in the case of calculations of the basic protection functions of the substation.

It is necessary to calculate the short-circuit currents to [15]:

- establish adequate sizing of the operating and interruption parts;
- define the thermal and mechanical stresses of the plant elements;
- calculate and select the protection system settings;
- carry out suitable protection for people and the plants.

When studying electric networks, it is important to define the short-circuit currents under the various operating conditions. In particular the maximum short-circuit currents are important for sizing the apparatus, the minimum short-circuit currents allow protection coordination to be checked:

The protection trip current must always be lower than the minimum short-circuit current at the point of connection. It must be remembered that a short-circuit causes passage of currents through the accidental or intentional connection making up the short-circuit itself and through the various components as far as the source and is therefore a potential cause of damage and fires [15].

As input data, the University provided information about the substation to which the designed switchgear will be connected. All the main parameters required for the calculation are presented below in Table 2.

Transformers:	**T1**	**T2**	**T3**
• Apparent power S_{Tx}, kVA:	630	25	160
• Short-circuit impedance u_{kTx}, %:	5.8	a) 21.2 (for 6kV) b) 1.2 (for 22kV) c) neglectable (for 35kV)	
Cable line:	**C1**		
• Length l, km:	0.1		
• Impedance per unit of length X_{C1}, Ohm/km:	0.078		
• Resistance per unit of length R_{C1}, Ohm/km:	0.194		
Upstream network:	**S1**		
• Voltage factor c:	1.1		
• Nominal voltage U_{S1}, kV:	0.4		
• Short-circuit current I_{UP}, A*:	190		

*Due to that fact, that it was not possible to find out the real value of short-circuit current from the upstream network side, it was decided to use I>> value from the relay from VSB substation as maximum expectable.

Table 2 – Input data for the calculation of the short-circuit currents.

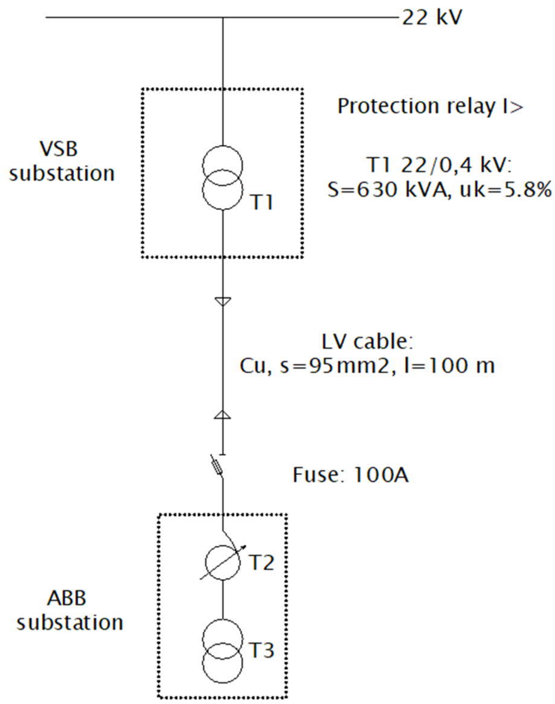

Figure 22 – Circuit diagram for calculations

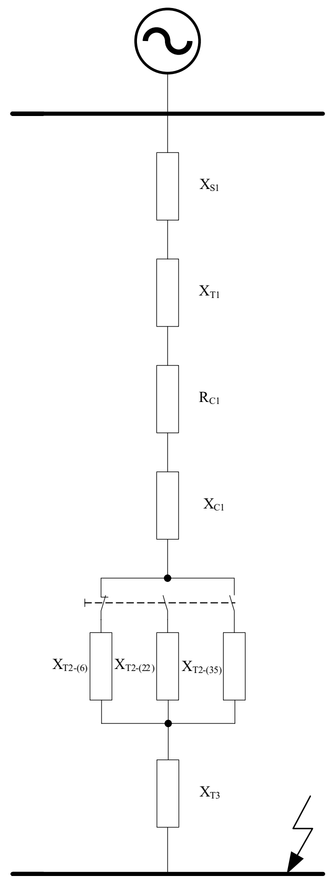

Figure 23 – Equivalent circuit diagram

To simplify the calculation procedure, the calculation method in relative units will be used. At the beginning, it is necessary to set the basis values:

Parameter	Value
• Basis apparent power S_V, kVA:	100
• Basis voltages U_{Vx}, kV:	6
	22
	35

Table 3 – Basis values for the calculation

1) Calculation of positive-sequence impedances.

1.1) Transformer T1:

$$X_{T1(1)} = \frac{u_{kT1} \cdot S_V}{100 S_{T1}}, \tag{1}$$

$$X_{T1(1)} = \frac{5.8 \cdot 100}{100 \cdot 630} = 9.206 \cdot 10^{-3}.$$

1.2) Transformer T2:

$$X_{T2-6(1)} = \frac{u_{kT2-6} \cdot S_V}{100 S_{T2}}, \tag{2}$$

$$X_{T2-6(1)} = \frac{21.2 \cdot 100}{100 \cdot 25} = 0.848.$$

$$X_{T2-22(1)} = \frac{u_{kT2-22} \cdot S_V}{100 S_{T2}}, \tag{3}$$

$$X_{T2-22(1)} = \frac{1.2 \cdot 100}{100 \cdot 25} = 0.048.$$

$$X_{T2-35(1)} = \frac{u_{kT2-35} \cdot S_V}{100 S_{T2}}, \tag{4}$$

$$X_{T2-35(1)} \approx 0.$$

1.3) Transformer T3:

$$X_{T3(1)} = \frac{u_{kT3} \cdot S_V}{100 S_{T3}}, \tag{5}$$

$$X_{T3(1)} = \frac{6.27 \cdot 100}{100 \cdot 160} = 0.039.$$

1.4) Cable line C1:

$$r_{C1(1)} = R_{C1} \cdot l_1 \cdot \frac{S_V \cdot 10^{-3}}{U_C^2}, \tag{6}$$

$$r_{C1(1)} = 0.194 \cdot 0.1 \cdot \frac{100 \cdot 10^{-3}}{0.4^2} = 0.012,$$

$$x_{C1(1)} = X_{C1} \cdot l_1 \cdot \frac{S_V \cdot 10^{-3}}{U_C^2}, \tag{7}$$

$$x_{C1(1)} = 0.078 \cdot 100 \cdot \frac{100 \cdot 10^{-3}}{0.4^2} = 4.875 \cdot 10^{-3}.$$

1.5) Upstream network S1:

$$S_k = \sqrt{3} \cdot U_{S1} \cdot I_{UP}, \tag{8}$$

$$S_k = \sqrt{3} \cdot 0.4 \cdot 190 = 131.636\ kVA,$$

$$x_{S1} = \frac{c \cdot S_V}{S_k}, \tag{9}$$

$$x_{S1} = \frac{1.1 \cdot 100}{131.64} = 0.836.$$

1.6) Equivalent resistance:

$$Z_{\Sigma-6(1)} = r_{C1(1)} + i \cdot (x_{T1(1)} + x_{T2-6(1)} + x_{T3(1)} + x_{C1(1)} + x_{S1(1)}) \tag{10}$$

$$Z_{\Sigma-6(1)} = 0.012 + i \cdot (9.206 \cdot 10^{-3} + 0.848 + 0.039 + 4.875 \cdot 10^{-3} + 0.836) = \\ = 0.012 + 1.737i,$$

$$Z_{\Sigma-22(1)} = r_{C1(1)} + i \cdot (x_{T1(1)} + x_{T2-22(1)} + x_{T3(1)} + x_{C1(1)} + x_{S1(1)}) \tag{11}$$

$$Z_{\Sigma-22(1)} = 0.012 + i \cdot (9.206 \cdot 10^{-3} + 0.048 + 0.039 + 4.875 \cdot 10^{-3} + 0.836) = \\ = 0.012 + 0.937i,$$

$$Z_{\Sigma-35(1)} = r_{C1(1)} + i \cdot (x_{T1(1)} + x_{T2-35(1)} + x_{T3(1)} + x_{C1(1)} + x_{S1(1)}) \tag{12}$$

$$Z_{\Sigma-35(1)} = 0.012 + i \cdot (9.206 \cdot 10^{-3} + 0 + 0.039 + 4.875 \cdot 10^{-3} + 0.836) = \\ = 0.012 + 0.889i$$

where $Z_{\Sigma-6(1)}$ – resistance of the branch for the voltage level 6 kV, p.u.;

$Z_{\Sigma-22(1)}$ – resistance of the branch for the voltage level 22 kV, p.u.;

$Z_{\Sigma-35(1)}$ – resistance of the branch for the voltage level 35 kV, p.u.

2) Current values in relative units:

$$I_{VA1} = \frac{S_V}{\sqrt{3} \cdot U_{V1}}, \tag{13}$$

$$I_{VA1} = \frac{100}{\sqrt{3} \cdot 6} = 9.623\ A,$$

$$I_{VA2} = \frac{S_V}{\sqrt{3} \cdot U_{V2}}, \tag{14}$$

$$I_{VA2} = \frac{100}{\sqrt{3} \cdot 22} = 2.624\ A,$$

$$I_{VA3} = \frac{S_V}{\sqrt{3} \cdot U_{V3}}, \tag{15}$$

$$I_{VA3} = \frac{100}{\sqrt{3} \cdot 35} = 1.65\ A.$$

3) 3-phase short-circuit currents:

$$I''_{k3A1} = \frac{c \cdot I_{VA1}}{|Z_{\Sigma-6(1)}|}, \tag{16}$$

$$I''_{k3A1} = \frac{1.1 \cdot 9.623}{|0.012 + 1.737i|} = 6.094\ A,$$

$$I''_{k3A2} = \frac{c \cdot I_{VA2}}{|Z_{\Sigma-22(1)}|}, \tag{17}$$

$$I''_{k3A1} = \frac{1.1 \cdot 2.624}{|0.012 + 0.937i|} = 3.081\ A,$$

$$I''_{k3A3} = \frac{c \cdot I_{VA3}}{|Z_{\Sigma-35(1)}|}, \tag{18}$$

$$I''_{k3A1} = \frac{1.1 \cdot 1.65}{|0.012 + 0.889i|} = 2.041\ A.$$

The calculation of short-circuit currents is the base from which the formation of the protection system of the entire substation begins. Since any designed switchgear or substation is a complex structure to design, there are a huge number of different accidents or abnormal working conditions that can occur. To simplify design processes, the IEEE organization has standardized a set of possible accidents using numerical codes. Table 4 shows the numerical codes of protection functions and their definition according to the IEEE C 37.2:2008 standard.

IEEE code	Function	IEEE code	Function
12	Over-speed	50	Instantaneous overcurrent
14	Under-speed	50G	Instantaneous overcurrent (on ground conductor)
19	Reduced voltage start	50ARC	Arc fault
21	Distance	51	Time overcurrent
23	Temperature control	51G	Time overcurrent (on ground conductor)
24	V/Hz (overfluxing)	55	Power factor
25	Synchronism check	58	Rectifier failure
27	Undervoltage	59	Overvoltage
28	Flame safety detection	64	Ground fault
30	Annunciator	65	Speed governing
32	Directional (reverse) power	66	Starts per hour / time between starts
37	Undercurrent/underpower	67	Directional overcurrent
38	Bearing overtemperature	68	Blocking
40	Loss of excitation	74	Alarm
43	Manual transfer/selector	78	Phase angle / out-of-step
46	Current unbalance	79	Automatic reclose
46R	Broken conductor	81H/81L	Overfrequency/Underfrequency
47	Phase reversal	81R	Rate of frequency change
48	(Motor) stall	86	Lockout or Auxiliary
49	Thermal overload	87	Differential

Table 4 – Numerical codes for protection functions according to IEEE [16]

As can be seen from the SLD of the designed substation, when talking about protection, it is necessary to consider two main feeders, namely the incoming one, which contains a transformer, and the outgoing one, which we take as a line feeder. Since the calculation of protective functions and programming of the relay occupy a separate large paragraph in the work on the design of the substation and require detailed study, this thesis will cover the main and basic protection functions that must be considered for the above types of connection, as well as ways to ensure these protections.

The line protection is adequate when overload protection is provided, and it is possible to detect multi-phase short-circuit and single-phase earth-fault. Thus, protection is extremely simple and generally limited to the following protection functions:

- 49 thermal protection against overload;
- 51 overcurrent protection against high impedance faults;
- 50 overcurrent protection against short-circuit;
- 87L differential line protection;
- 50N protection against ground faults.

The thermal protection (49) was never provided in the past as it required installation of a particular relay with at considerable cost. With the advent of digital protections, this protection is generally provided in all relays and therefore allows good and adequate protection to be obtained, avoiding overtemperatures (with consequent reduction of life) of the lines. It is also often used only in alarm for monitoring the lines.

Protection functions (51/50) are against non-directional over-currents and several thresholds are present in the relay (of which at least one with inverse time). These thresholds must be set for currents lower than the minimum fault current and be selective with the load side protections. The ground protection is generally against overcurrent supplied by type ring CTs to guarantee great sensitivity and be able to identify ground faults even of resistive type. Two types of protections can be used:

- 51G: non-directional ground overcurrent: applicable when the capacitive contribution of the network load side is lower than the setting to be set on the protection;
- 67G: directional ground overcurrent: applicable to any network but with the caution that a set of three VTs with star connection must be present on the switchgear to be able to have the homopolar voltage which allows a reference for the direction of the fault current to be established [15].

A transformer is a two-way type of device, i.e. the flow of energy can be in two directions without distinction. This clarification is very important since in plants where there can be power which flows without distinction from the primary to the secondary or vice versa, it is necessary to prepare protections on both sides. If, on the other hand, the transformer is only used with power flow in one direction, the protection system against phase faults may only be provided on the power supply side. What has been stated is only valid for the protections against phase faults and is not valid for ground protections as the two homopolar circuits are generally independent and each one needs dedicated protection against ground faults.

The faults or abnormal operating conditions in transformers can be traced back to (and consequently the protection must recognize) the following:

- Overload;
- Short-circuit;
- Primary side ground fault;
- Secondary side ground fault.

In their turn, these abnormal operating conditions can be identified using different protection functions which can also be a reserve for each other, for example, short-circuit can be identified using overcurrent protections and/or differential protections.

The protection functions to be provided for a transformer are:

- 49 thermal overload protection;
- 51 overcurrent protection with inverse time;
- 51 or 50t secondary side short-circuit overcurrent protection;
- 50 primary side overcurrent short-circuit protection;
- 87T differential transformer protection;
- 51G primary side overcurrent ground fault protection;
- 51G secondary side overcurrent ground fault protection;
- 26 overtemperature protection;
- 63 overpressure protection (only for oil transformers).

Other protections can be provided for particular applications or for high-power transformers. These protection functions are:

- 24 overflux protection;
- 46 negative sequence overcurrent protection;
- 87N restricted differential ground fault protection (for one or both windings);
- 51G tank protection.

As shown in the list, several overcurrent protection thresholds are usually provided in order to be able to select settings that use both the temporary type selectivity (functions 51 or 50t) and the current type selectivity (50) and at the same time provide the transformer with adequate overload and the ability to obtain good selectivity with load-side protection.

In the past, differential protection was usually installed on transformers with significant power (more than 5 MVA). Some types of protection relays (for example, REF 54x) allow you to activate differential protection as a basis, and therefore it can be activated at no additional cost, even on small transformers [15].

5 Choosing of Primary Electrical Equipment

In this Chapter, it is necessary to select the main electrical equipment based on the requirements of the University, and it is also important that the selected equipment meets the requirements of the IEC 62271:2020 SER High-voltage switchgear and controlgear standard.

5.1 Choosing of medium voltage (MV) step-up transformer

According to the design assignment, the medium voltage step-up transformer was initially set, therefore, it does not need additional substantiation. A transformer was adopted in the project with the parameters given in Table 5.

Parameters	Medium voltage	Low voltage
Rated voltage, kV	35 ± 2×2,5%	0,4
Rated current, A	2,64	231
Rated power, kVA	160	
Winding connection	Dyn-1	
Short-circuit impedance, %	6,37	
Short-circuit losses (P_K), kW	3,335	
No-load losses (P_0), kW	0,48	
Type of cooling	AN	

Table 5 – Parameters of the step-up MV transformer

5.2 Choosing of medium voltage circuit breakers

In compliance with IEC 62271-100 circuit-breaker suitable for a given duty in service is best selected by considering the individual rated values required by load conditions and fault conditions.

The duty imposed by the fault conditions with which a circuit-breaker is required to deal should be determined by calculating the fault currents at the place where the circuit-breaker is to be located in the system, in accordance with some recognised method of calculation.

When selecting a circuit-breaker, due allowance should be made for the likely future development of the system as a whole, so that the circuit-breaker may be suitable not merely for immediate needs but also for the requirements of the future.

Circuit-breakers which have satisfactorily completed type tests for a combination of rated values (i.e. voltage, normal current, making and/or breaking current) are suitable for any lower rated values (with the exception of rated frequency) without further testing. Switching of inductive loads (magnetising currents of transformers, high-voltage motors and shunt reactors) are specified in IEC 62271-110 [17].

According to the design assignment, it is necessary to select two medium voltage circuit breakers. Taking into account the fact that the actual operating current of the substation in any of its operating modes (other than 0 kV) will be no higher than 1 A, we can conclude that any medium voltage circuit breaker of the desired voltage class will be suitable.

The circuit breakers of the VD4 series manufactured by ABB, with a rated voltage of 24 kV, were accepted for consideration.VD4 medium voltage circuit breakers use vacuum interrupters embedded in the poles. This construction technique makes the poles of the circuit breaker particularly sturdy and protects the interrupter from shocks, dust and condensation. The vacuum interrupter houses the contacts and forms the interruption chamber. The main parameters of the selected circuit breakers are shown in the table below.

Circuit breaker		VD4 24						
Standards	IEC 62271-100	•						
Rated voltage	Ur [kV]	24						
Rated insulation voltage	Us [kV]	24						
Withstand voltage at 50 Hz	Ud (1 min) [kV]	50						
Impulse withstand voltage	Up [kV]	125						
Rated frequency	fr [Hz]	50-60						
Rated thermal current (40 °C)	Ir [A]	630	630	1250	1250	1600	2000	2500
Rated breaking capacity (rated symmetrical short-circuit current)	Isc [kA]	16	16	16	16	16	16	–
		20	20	20	20	20	20	–
		25	25	25	25	25	25	25
		–	–	31.5	–	31.5	31.5	31.5
Admissible rated short-time withstand current (3s)	Ik [kA]	16	16	16	16	16	16	–
		20	20	20	20	20	20	–
		25	25	25	25	25	25	25
		–	–	31.5	–	31.5	31.5	31.5
Making capacity	Ip [kA]	40	40	40	40	40	40	–
		50	50	50	50	50	50	–
		63	63	63	63	63	63	63
		–	–	80	–	80	80	80

Table 6 – Parameters of VD4 vacuum circuit breaker

Benefits and features of VD4 [18]:

- The most versatile and powerful solution among medium voltage vacuum circuit breakers;
- Ideal for all applications (e.g., capacitor bank switching, marine, GOST);
- Cassettes and module systems available for OEMs and panel builders to create their own solutions;
- Fully interchangeable — both for overall dimension and electrical diagram — with ABB VD4 medium voltage gas circuit breaker;
- Only one common plug-and-play actuator (EL type) from 12 kV to 36 kV with a wide range of accessories, safety locks and interlocks, and with same family feeling of ABB low voltage series EMAX;
- Vacuum interrupters embedded in poles for protection against humidity, shocks and dust;
- Modular spring-operated mechanical actuator ensuring easy operation even without auxiliary supply;
- 30,000 mechanical operations on most ratings;
- Rated at up to up to 46 kV, 4,000 A, 63 kA.

As can be seen from table 6, the minimum value of the operating current for a circuit breaker of this type is 630 A, which is many times higher than the operating current of the designed substation. Thus, it can be argued that thermal and electrodynamic resistance for this circuit breaker will be provided.

5.3 Choosing of medium voltage disconnectors

In compliance with IEC 62271-102:2018 for the selection of disconnectors and earthing switches, the following conditions and requirements at site should be considered:
continuous current load and overload conditions;

- existing fault conditions;
- static and dynamic terminal loads resulting from the substation design;
- use of rigid or flexible conductors to be connected to the disconnector or earthing switch or to which the separated contact is mounted;
- environmental conditions (climate, pollution, etc.);

- altitude of the substation site;
- required operational performance (mechanical endurance);
- switching requirements (bus-transfer current switching by disconnectors, induced current switching by earthing switches, short-circuit making capacity of earthing switches).

When selecting a disconnector or earthing switch, due allowance should be made for the likely future development of the system as a whole so that the disconnector or earthing switch is suitable not merely for immediate requirements, but also for those of the future.[19]

According to the design assignment, in this case it is necessary to choose two types of disconnectors:

1) 35 kV disconnector with earthing blades for incoming connection;
2) Six 24 kV disconnectors for the remaining parts of the designed substation.

As mentioned above, since the substation's operating current is of the order of 1 A, any disconnectors from the lower range of operating currents for a given voltage level will be suitable. The disconnectors of the OW series manufactured by ABB, with a rated voltage of 24 kV and 36 kV, were accepted for consideration.

Disconnectors for voltage 36 kV

Type		OWIII30/6-2 OWIII30/6UD-2 OWIII30/6UG-2	OWIII30/12-2 OWIII30/12UD-2 OWIII30/12UG-2	OWIII30/16-2 OWIII30/16UD-2 OWIII30/16UG-2
Rated voltage [kV]		36		
Frequency [Hz]		50		
Righted power frequency withstand voltage [kV]	to earth and between poles	70		
	between contacts	80		
Lightning impulse withstand voltage [kV]	to earth and between poles	170		
	between contacts	195		
Rated continuous current [A]		630	1250	1600
Rated peak withstand current [kA]		50	80	80
Rated short-time withstand current [kA]	1 s	-	31,5	31,5
	3 s	20	-	-

Table 7 – Parameters of the disconnector on 36 kV with earthing switch (UD)

Disconnectors for voltage 17,5 and 24 kV

Type		OWIII17,5/6-1 OWIII17,5/6UD-1 OWIII17,5/6UG-1	OWIII17,5/12-1 OWIII17,5/12UD-1 OWIII17,5/12UG-1	OWIII20/6-1 OWIII20/6UD-1 OWIII20/6UG-1	OWIII20/6-2 OWIII20/6UD-2 OWIII20/6UG-2	OWIII20/6-2/160 OWIII20/6UD-2/160 OWIII20/6UG-2/160	OWIII20/8-1 OWIII20/8UD-1 OWIII20/8UG-1	OWIII20/10-1 OWIII20/10UD-1 OWIII20/10UG-1	OWIII20/8-2 OWIII20/8UD-2 OWIII20/8UG-2	OWIII 20/10-2 OWIII20/10UD-2 OWIII20/10UG-2	OWIII20/12-1 OWIII20/12UD-1 OWIII20/12UG-1
Rated voltage [kV]		17,5		24							
Frequency [Hz]		50									
Righted power frequency withstand voltage [kV]	to earth and between poles	38		50							
	between contacts	45		60							
Lightning impulse withstand voltage [kV]	to earth and between poles	95		125							
	between contacts	110		145							
Rated continuous current [A]		630	1250	630			800	1000	800	1000	1250
Rated peak withstand current [kA]		40	40	50	63	40	50	50	63	63	80
Rated short-time withstand current [kA]	1 s	16	16	-	25	16	-	-	25	25	31,5
	3 s	-	-	20	-	-	20	20	-	-	-

Table 8 – Parameters of the disconnector on 24 kV without earthing switch (without UD)

Benefits and features of OW series disconnectors [20]:

- Rated voltages 7,2 – 36 kV;
- Rated currents 630 – 1600 A;
- High short-time withstand current up to 31,5 kA/1s; peak value up to 80 kA;
- Single or three phase design (OWI, OWIII);

- Available with earthing switches on both sides;
- Operated with manual or motor drives;
- Many ways of coupling with drive by common gears, couplers and rods;
- Vertical-break opening;
- Fixed terminals for connection on both sides;
- Durable porcelain or resin insulators;
- Powder coated steel frame;
- Applicable standards IEC 62271-1, IEC 62271-102;
- Wide range of applications for available types;
- Safe and visible isolating gap in open position;
- Proven and reliable design;
- High mechanical endurance;
- Installation position: horizontal or vertical;
- Suitable for new installations or retrofit;
- Easy to install and commission;
- Minimal maintenance requirements;
- Smart grid and network automation ready;
- Possibility to customize for tailor made solution;

5.4 Voltage measuring transformers

In this project, two types of voltage measuring transformers should be used, the first type is 35 kV transformers, and the second type is 24 kV transformers. Taking into account the fact that at the beginning of the design, 35 kV voltage measuring transformers were already purchased, they do not need to be selected and additional justification and are accepted for design. The table below shows the parameters of voltage measuring transformers.

Primary voltage, [V]	Secondary voltage		
	voltage, [V]	accuracy	burden, [VA]
22 000/√3	100/√3	0.5	15;25;50

Table 9 – Parameters of the voltage measuring transformers (22 kV)

5.5 Current measuring transformers

Since the operating current flowing through the substation bus bars has an extremely low value, this directly affects the possible accuracy of current transformers. It was determined that it is not possible to use current transformers from the nominal range for given voltage level, it was decided to order measuring current transformers of a special configuration that would meet all required conditions. The following transformers were designed at the ABB (ELDS) factory in Brno.

Type: KON24 1/1

Standard: IEC 61869-2 Ins.Level: 24/50/125kV Altitude: 1.0 km

Ith: 0.5kA / 1s Idyn: 1.3kA Temp.: 40°C f: 50Hz

Core	Ratio	Ext	Class	Burden	Ukp/Ual	Rct	Io/Ial	Kssc	Rb
S1- S2	1/1 A	120%	0.5S	0.5VA					Ω

Figure 24 – Parameters of the designed current transformers

6 Design of the Control and Protection Cabinet

A Control Cabinet (CP) solution is designed to provide to control the associated line or transformer feeders through MV indoor and outdoor switchgear at various primary distribution/zonal substations. The CP is one of the most important equipment of the substation as it works as a shield guard for entire substation equipment's and electrical network.

In this case, the main purpose of the control and protection panel is to regulate the voltage throughout the substation, to implement local and remote control over the equipment, it is assumed to install a selector switch between local and remote mode. A similar principle will be used for monitoring and setting the required voltage level.

6.1 Control scheme

The initial stage of developing the control and protection was to draw up a scheme how the control of the substation will be implemented. For this purpose, the SLD was divided into three zones, where each zone is controlled by one of the IEDs.

The first zone includes the MCB 400 V and autotransformer. This is the most important part of the substation, where the voltage level is being chosen. For this purpose, the REU615 will be used. REU615 is a voltage protection and control relay for voltage and frequency-based protection in utility and industrial power distribution systems, including networks with distributed power generation. For the purposes of voltage regulation and monitoring the REU615 is an ideal solution. The configuration of the REU615 is shown below.

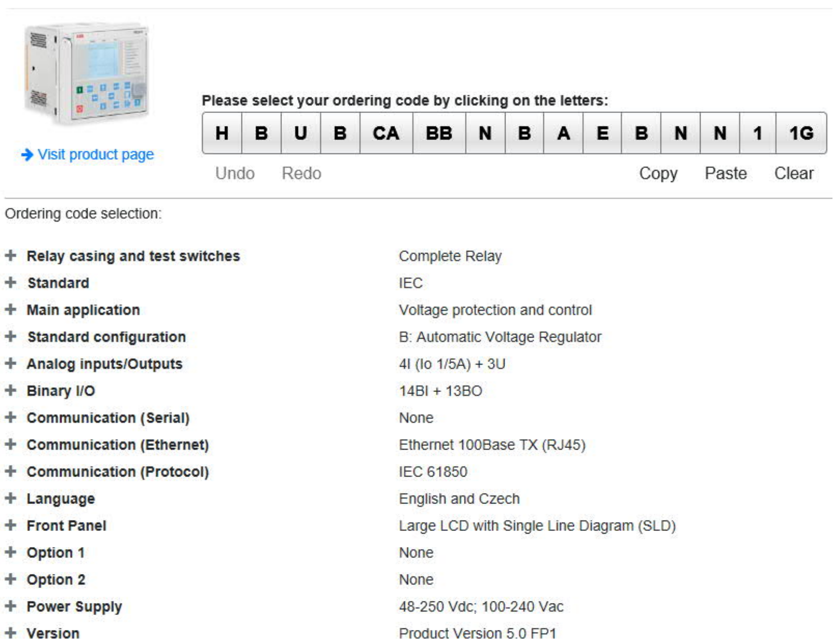

Figure 25 – Configuration and ordering code of REU615

Benefits and features of REU615 [21]:

- Exclusively designed for automatic and manual voltage regulation, or alternatively for busbar under voltage and overvoltage supervision, load shedding and restoration;
- Ready-made standard configurations for fast and easy setup with tailoring capabilities;
- Withdrawable plug-in unit for swift installation and testing;
- Large graphical display showing customizable SLDs, accessible either locally or through an easy-to-use web-browser-based HMI;

- Extensive life-cycle services;
- Extensive range of protection and control functionality for busbar voltage supervision, load shedding and restoration, including over frequency and under frequency protection for power generators and another AC equipment;
- Automatic voltage regulation of power transformers with a motor-driven on-load tap changer;
- Optional arc protection and high-speed outputs (not with automatic voltage regulator);
- Supports IEC 61850 Editions 1 and 2, including HSR and PRP, GOOSE messaging and IEC 61850-9-2 LE for less wiring and supervised communication;
- IEEE 1588 V2 for high-accuracy time synchronization and maximum benefit of substation-level Ethernet communication;
- Supports Modbus, DNP3 and IEC 60870-5-103 communication protocols.

The second zone is determined by the remaining equipment of the incoming feeder. Namely, a step-up power transformer, a disconnector with 35 kV earthing switch, a 24 kV medium voltage circuit breaker and two 24 kV disconnectors. IED RET620 was selected to control the listed equipment. RET620 is a dedicated transformer management relay for the protection, control, measurement and supervision of both power and step-up transformers, including power generator-transformer blocks, in utility and industrial power distribution systems. Compact and versatile two-winding power transformer protection relay with integration of protection, control, monitoring and supervision in one relay. The configuration of the RET620 is shown below.

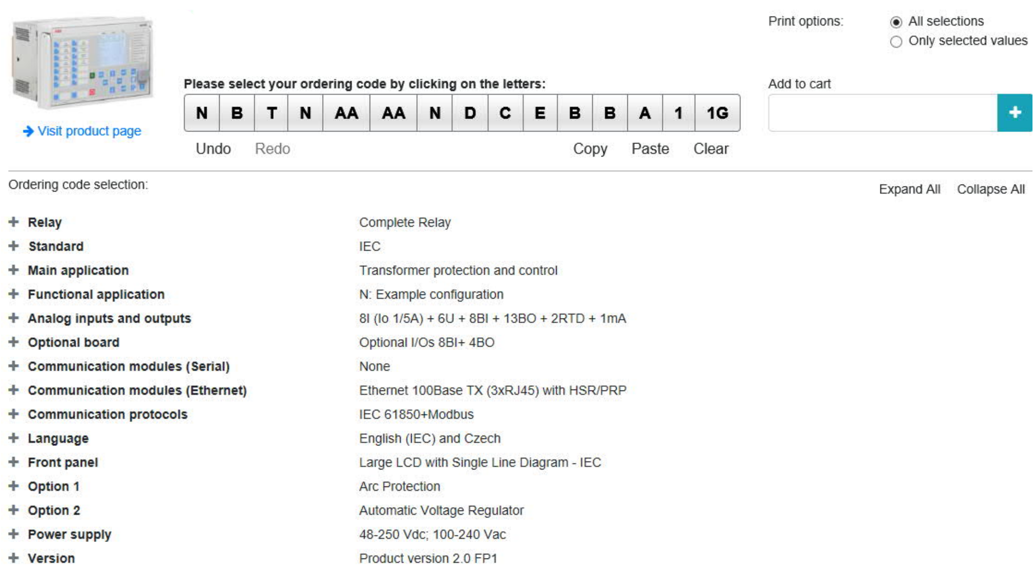

Figure 26 – Configuration and ordering code of RET620

Benefits and features of RET620 [22]:

- Extensive protection and control functionality;
- Functional scalability and extensive possibilities to easily tailor configurations to application-specific requirements;
- Withdrawable plug-in unit design for swift installation and testing;
- Large graphical display showing customizable SLDs, accessible either locally or through an easy-to-use web-browser-based HMI;
- Extensive life-cycle services;

- Extensive range of protection and control functionality for two-winding power transformers, including advanced and fast differential protection with high inrush stability;
- Supports various neutral earthing options, matching either high-impedance or numerical low-impedance restricted earth-fault principles;
- Optionally can also include automatic voltage regulation of power transformers with a motor-driven on-load tap changer and arc protection;
- Supports native IEC 61850 Edition 1 and 2, including redundancy HSR and PRP, GOOSE messaging and IEC 61850-9-2 LE for less wiring and supervised communication;
- Supports Modbus, DNP3 and IEC 60870-5-103 communication protocols and different time synchronization methods, including high-accuracy time synchronization via IEEE 1588 V2 Precision Time Protocol.

It is also an advantage that with using RET620 it is also possible to implement differential protection of the transformer in case of installation of a second current transformer on the low voltage side.

Considering the fact that the substation will mainly serve as a laboratory facility for various studies, the availability of the maximum possible number of protective functions is the most preferable, this is what determines the choice of IED data and their configuration.

The third zone includes all the remaining primary equipment. Since this part of the substation does not include special equipment that might require a special protection approach, such as a transformer, in this case the ideal solution would be to use REF620. REF620 is a dedicated feeder management relay for protection, control, measurement and supervision in utility and industrial power distribution systems, including radial, looped and meshed networks, with or without distributed power generation. Compact and versatile feeder protection relay solution with integration of protection, control, monitoring and supervision in one relay.

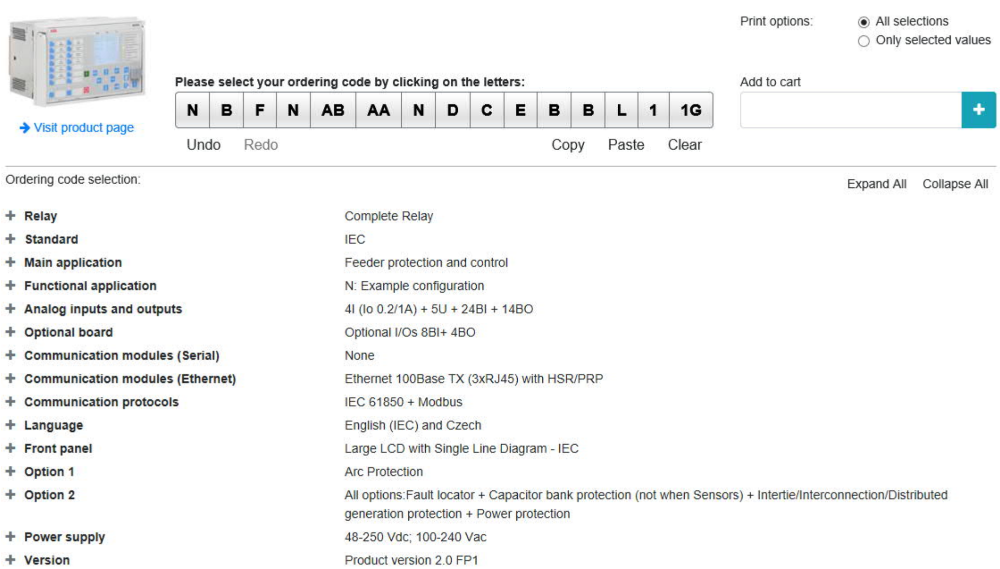

Figure 27 – Configuration and ordering code of REF620

Benefits and features [23]:

- Extensive protection and control functionality, either with sensors or conventional instrument transformers;

- Functional scalability and extensive possibilities to easily tailor configurations to application-specific requirements;
- Withdrawable plug-in unit design for swift installation and testing;
- Large graphical display for showing customizable SLDs, accessible either locally or through an easy-to-use web-browser-based HMI;
- Extensive life-cycle services;
- Wide range of protection and control functionality for incoming and outgoing feeders;
- Extensive earth-fault protection portfolio with unique multifrequency admittance-based protection for higher sensitivity and selectivity;
- Several optional functionality packages – advanced and fast fault location of short circuits and earth faults, interconnection protection for distributed power generation, capacitor bank, basic motor and arc protection;
- Supports native IEC 61850 Editions 1 and 2, including redundancy HSR and PRP, GOOSE messaging and IEC 61850-9-2 LE for less wiring and supervised communication;
- Supports Modbus, DNP3 and IEC 60870-5-103 communication protocols and for different time synchronization methods, including high-accuracy time synchronization via IEEE 1588 V2 Precision Time Protocol.

It is worth noting that RET620 and REF620 were provided with arc sensors when creating the configuration type, which can be used for educational purposes in order to demonstrate the protection capabilities of high-voltage equipment in cases of arc occurrence.

Ultra-fast clearing of arc flash faults in medium voltage (MV) switchgear panels is essential in controlling arc flash hazards. Reducing the arcing time through faster detection is the most practical way of reducing incident energy levels and improving workplace safety.

The complete control scheme is shown in the Annex A.

The next important step in the design of the control cabinet was the charting of external connection diagram. This diagram will allow us to most effectively analyze the mutual connections of the substation zone and the control and protection cabinet in order to maximize optimization. Based on the initial data, the control and protection cabinet should be in a different room from the substation, so the main questions are the competent distribution of secondary equipment between the substation and the cabinet, and the optimization of the number of wires and cables between them. It was determined that the best solution would be if RET and REF are located directly in the substation zone, while REU is installed in the control cabinet.

6.2 Interlocking concept

The next important stage in the development of secondary substation circuits is the interlocking concept. Since the designed substation should primarily serve educational purposes as a laboratory installation, it follows that it will primarily be operated by low-skilled personnel, namely students during various tests and measurements. It becomes important to create a concept that would prevent damage to the life and health of personnel, as well as damage to equipment as a result of erroneous actions or an emergency.

Starting from this chapter and in all others the graphical part is performed in the module Eplan Electric P8.

6.1.1 Emergency interlock

According to the design assignment, the designed substation should be surrounded by a Faraday cage, which should have two doors: one for the entrance of the maintenance personnel, and the other for access to the outputs of the step-up transformer for various experiments. For safety reasons, it is necessary to ensure that the substation is completely de-energized if any of the doors are opened by someone while the substation's busbars are energized.

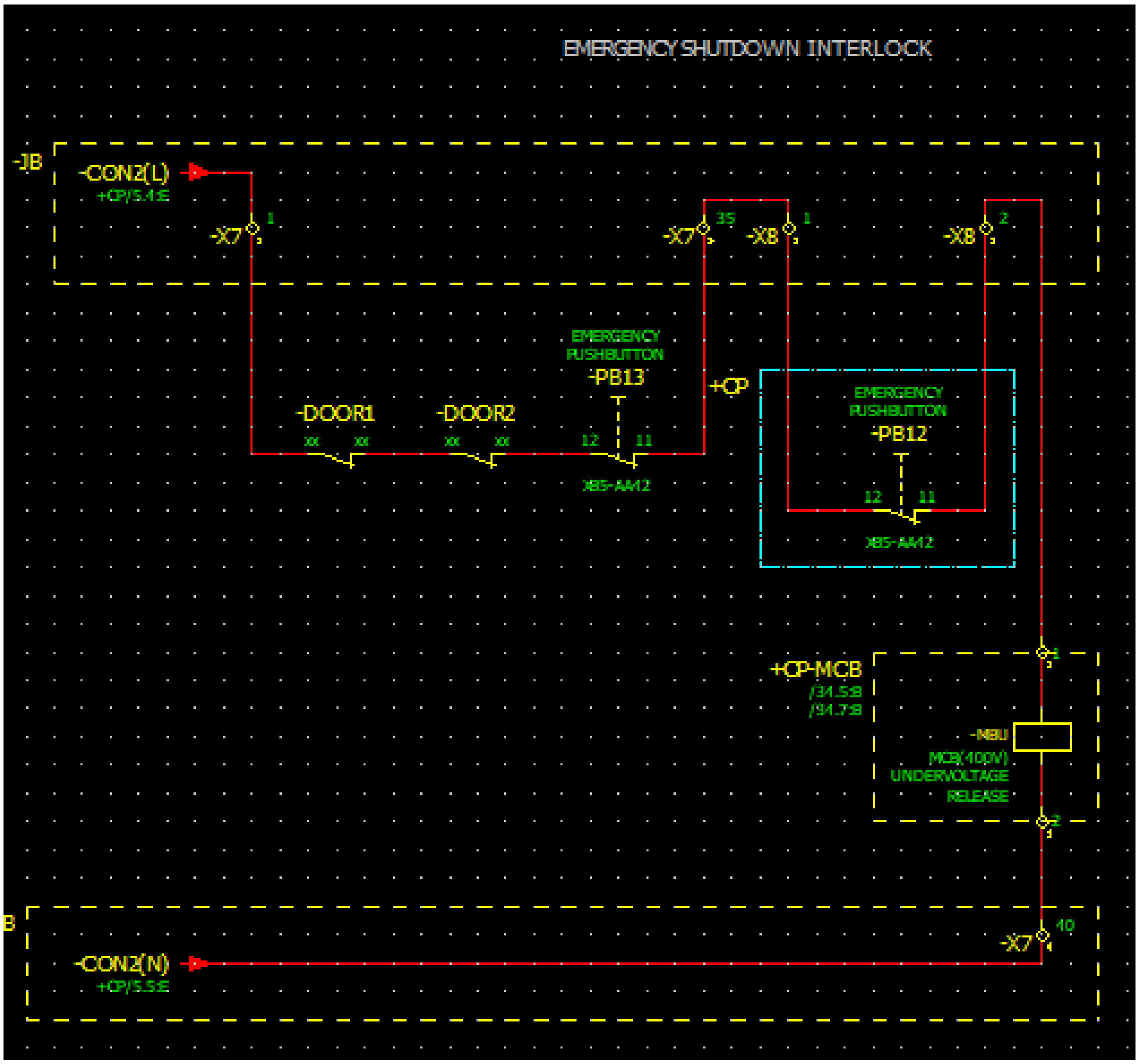

Figure 28 – Graphical representation of the emergency interlock

On the figure above is shown how the emergency interlock will be implemented. To provide additional security, it is assumed to use two emergency shutdown buttons(-PB12, -PB13), one of which will be located in the substation area (-PB13), and the other will be located on the front panel of the control cabinet (+CP-PB12).

6.1.2 Interlocks for the disconnectors

In this case, these interlocks are necessary to ensure the correct operation of the substation. The configuration of these interlocks is affected not only by which bus a particular disconnector is connected to, but also by which voltage level is selected as the operating voltage, since in the case of a substation operating at a voltage level of 35 kV and if the interlocks are incorrectly configured, this can lead to damage to all primary equipment as a result of overvoltage.

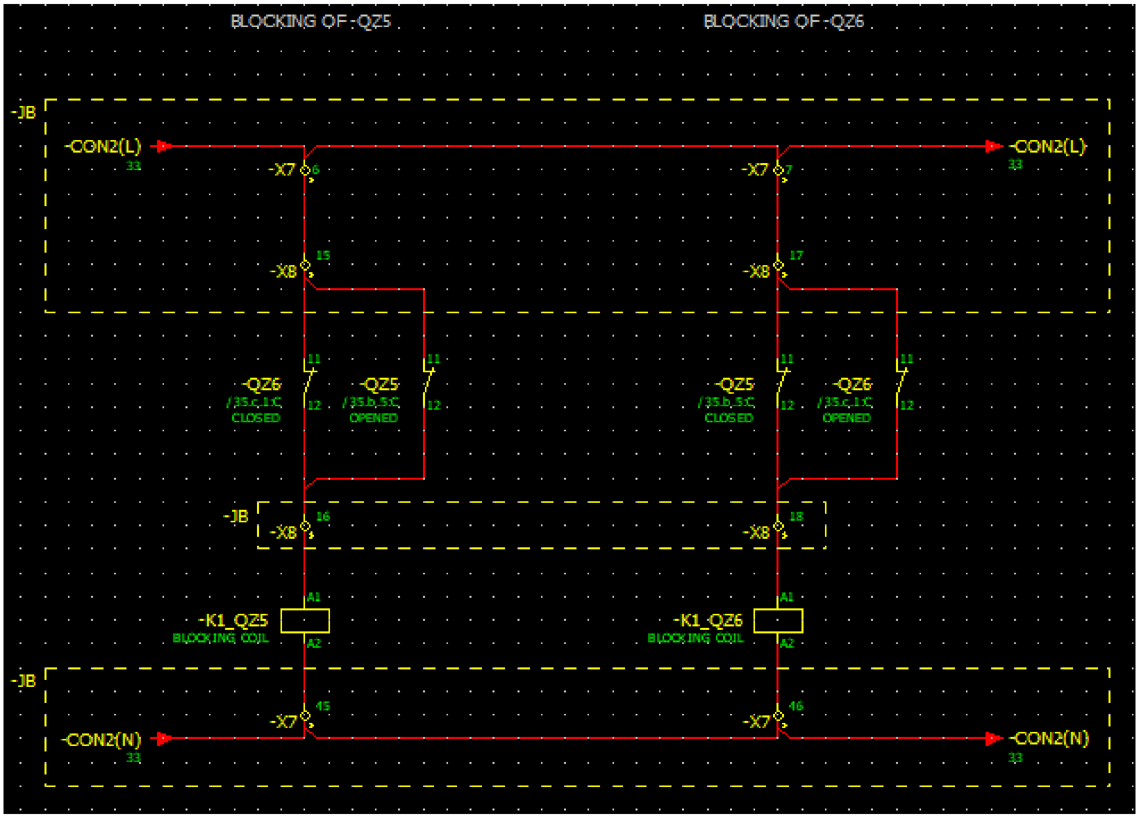

Figure 29 – Graphical representation of the interlock of the disconnectors (-QZ5) and (-QZ6)

The figure above shows an example of mutual blocking of two disconnectors that are connected to different bus bars. The basic principle is that if the disconnector QZ5 is in the closed position, then the disconnector (-QZ6) must be blocked for any interactions, this is valid for the disconnector (-QZ6) as well.

<u>6.1.3 Voltage regulation interlocks</u>

According to the design assignment, voltage regulation should be performed in two ways: using the buttons on the front panel of the control cabinet; and using REU615. To increase the voltage, all necessary interlocks must be provided to prevent damage to the equipment, while to reduce it, there is no need to create any interlocks.

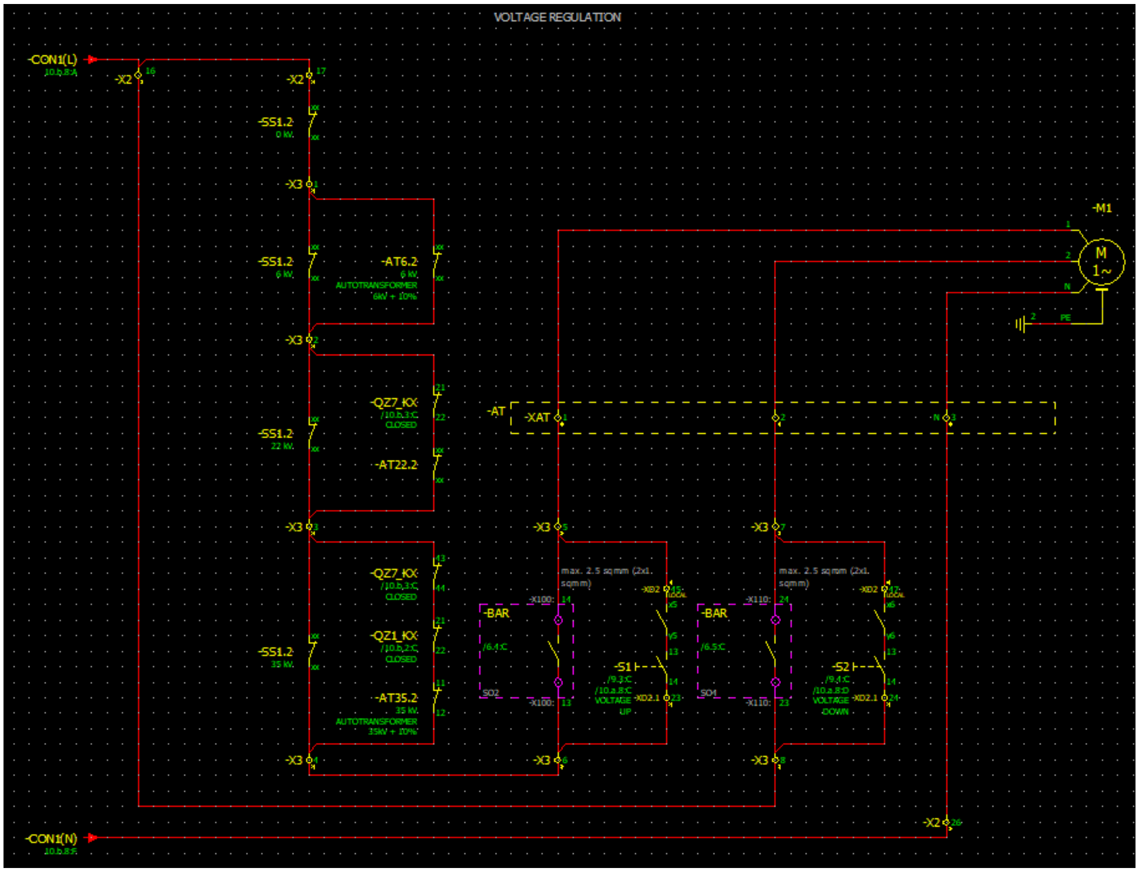

Figure 30 – Graphical representation of the interlock for the voltage regulation

Important in creating the concept of locks is also where they will be performed, since this directly affects the number of wires and cables that should be used in further control cabinet design

6.3 External connection diagram

The next step after the interlocking concept was to draw up a diagram of external connections, since in the future it will be used to determine which equipment will be located directly in the control cabinet, and which should be located in the substation area. At the first stage of drawing up the diagram, the proposed design site was divided into 2 parts, one of which is assigned to the zone where the control cabinet, the autotransformer and the MCB on 400 V will be located, the second part includes all the primary equipment and 2 protective devices (RET and REF)

The main principle determining the drawing of the diagram was the calculation of mutual connections between the cabinet area and the substation, since the main task of this diagram is to pre-optimize the number of connections in order to use this in the future when designing the control cabinet.

Main ways of optimization:

1. Use of auxiliary relays in the presence of multiple identical signals from the same element, for example, the disconnector (-QZ7) simultaneously sends three closed status signals, so it is advisable to use an auxiliary relay to transfer the signal to the control cabinet area once, and then to distribute it along the necessary circuits.

2. Avoiding unnecessary spending on wiring (performing interlocks where it is most reasonable), for example, those interlocks that involve connecting only those elements that are located in the substation area, it is not advisable to take out to the control cabinet area and vice versa.

Based on these assumptions, the external connection diagram was drawn (Annex B), in which the green marked connection from the substation area towards control cabinet, the red marked connections from the control cabinet zone towards switchgear area, and black denotes the mutual connections within any of the zones. Using this diagram, the control cabinet design process is noticeably simplified, which will be described further.

6.4 Front panel layout

In this section, it is necessary to develop a concept for the layout of auxiliary equipment on the front door of the control cabinet. To do this, it is important to define all the equipment that should be placed on the front panel. Since based on the described above, it was decided that only one IED will be located in the control cabinet, this decision is taken for development in the layout. In addition to the IED in the front panel of the control cabinet should also be located: analog voltmeter for measuring voltage in the range of 0-35 kV; the selector switches which will be used to select local/remote operation mode, the operating voltage level and for voltage measurement with using of analog voltmeter; control pushbuttons for operation of the primary equipment (opening/closing element), buttons for increasing and decreasing of the voltage level, and LEDs indicators which will show the position of the contacts of all primary equipment. The final layout is shown in Annex C.

6.5 Design of the main circuits of the control cabinet

This part describes the design process for all secondary circuits in the control cabinet. In total, there are 7 different types of circuits that can be taken into consideration:

1) Power supply circuits that serve to distribute energy to other circuits in the cabinet;
2) Protection circuits, which are responsible for monitoring the signals that are received at the IED from the main electrical equipment;
3) Control circuits, which serve to power the coils of all primary electrical equipment, are responsible for commands received from the relay to open/close the element and to adjust the voltage level;
4) Signal circuits, which serve for powering of the indication LED, which in turn indicate the position OPEN/CLOSED for all circuit breakers, earthing switch and disconnectors;
5) Spring charge circuits of motors for charging the MV circuit breaker springs, these motors are responsible for charging the springs necessary for the correct operation of the circuit breaker;
6) Voltage metering circuits to which voltage measuring transformers are connected;
7) Current metering circuits to which current measuring transformers are connected.

6.5.1 Power supply circuits design

The first stage in the design of control cabinet circuits is to determine the level of their supply voltage. Because this parameter is crucial for all the secondary equipment that will be accepted for use in the control cabinet in the future. According to the design assignment and the requirements of the University, 230 V AC is preferred as the supply voltage for all circuits, and it was accepted for further design.

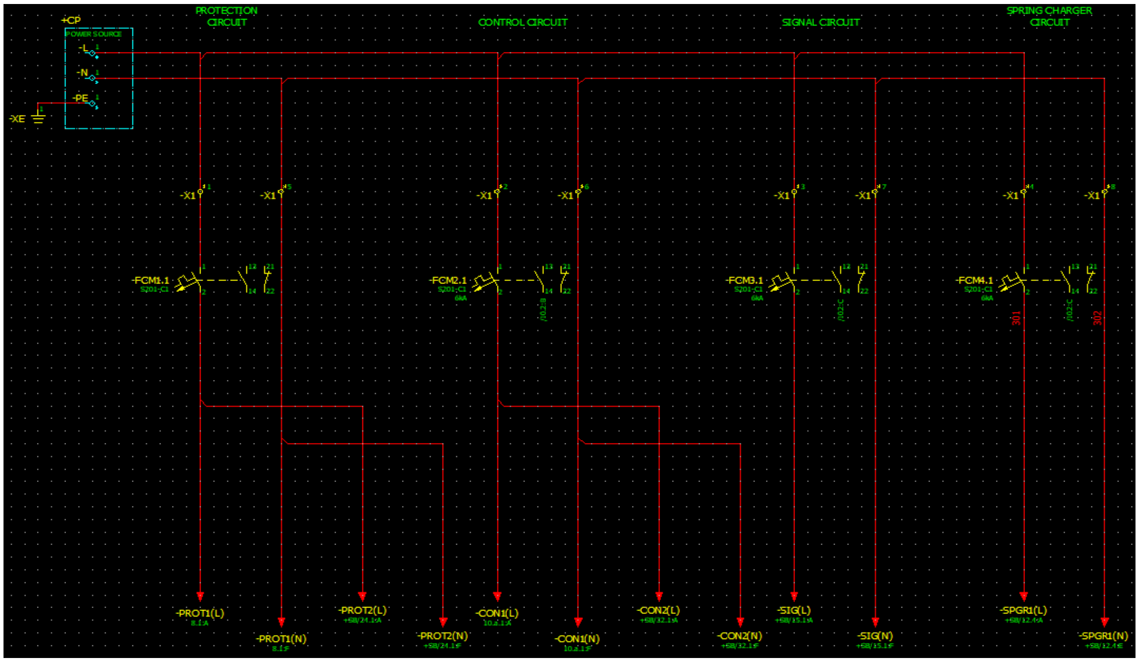

Figure 31 – Graphical representation of the supply circuits of the control cabinet

6.5.2 Protection circuits design

The purpose task of these circuits is to collect statuses from all primary and from some of secondary equipment. Based on this information, it is possible to program all IED's that will provide direct protection of equipment in the future. This is necessary to prevent possible accidents as a result of improper actions of the staff, as well as to demonstrate the work of various protections for students in purpose of education.

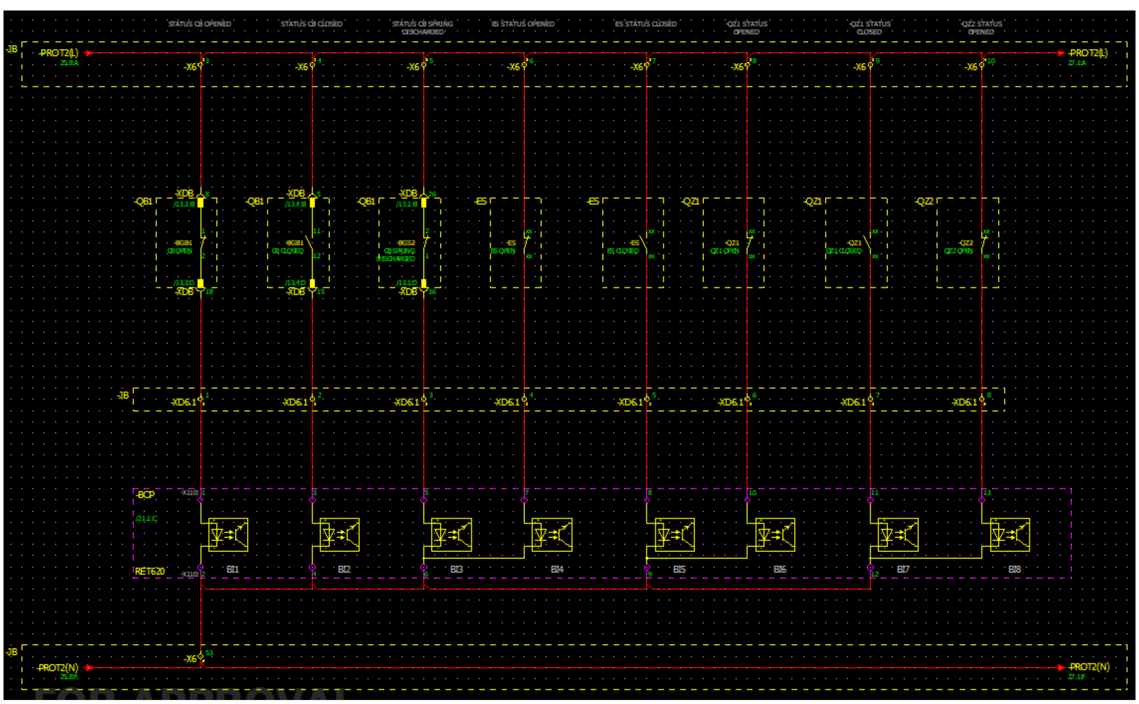

Figure 32 – Example of graphical implementation of statuses wired to RET620's binary inputs

6.5.3 Control circuits design

The main purpose of control circuits is to transmit commands from the outputs of the IEDs to the operating coils of medium-voltage circuit breakers, as well as to the operating coils of disconnectors. They also serve to increase/decrease the voltage with using of the REU615. Since the design assignment specified that each element must have local and remote control capability, each of the relay outputs bypassed by contact of the auxiliary relay that checks whether the local operation mode was selected on the selector switch in series with the pushbutton that refers to this element. In the figure below, an example of control circuits for a medium-voltage circuit breaker (-QB1) can be seen. The control circuits for all other breakers were performed in the same way.

From the Figure 33 it can be seen that for the circuit breaker the trip circuit supervision (TCS) function was used.

In a protection system the trip circuit of the circuit breaker is crucial. If an interruption occurs in the trip circuit a possible network fault will not be disconnected and would have to be cleared by another protection upstream in the power system. The supervision function is particularly important when there is only one tripping coil and CB tripping circuit is vital. For instance, for generator circuit breakers or any other important circuit breaker in distribution networks. The supervision module type TCS is intended for a continuous supervision of circuit breaker trip circuit and to give an “TCS not healthy” for CB CLOSE ENABLE, faults on the trip-coil or its wires independent of the breaker position, faults on the breaker auxiliary contacts and faults in the supervision relay itself.

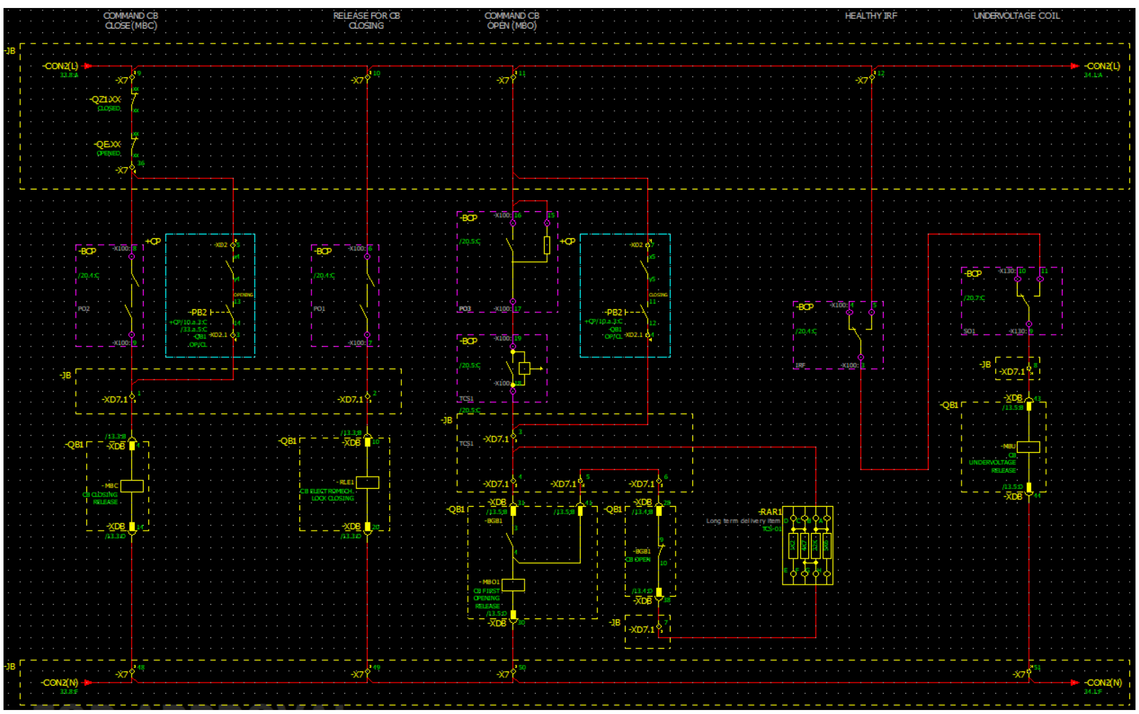

Figure 33 – Example of graphical implementation of the control circuits for the circuit breaker (-QB1)

6.5.4 Signal circuits design

These circuits only serve to indicate the position occupied by a particular element. In this project were used LED indicators that change color depending on whether the considered element is in the closed or opened position, so a green light signal was accepted for the open position, while a red light was accepted for the closed position. An example of signal circuits is shown below.

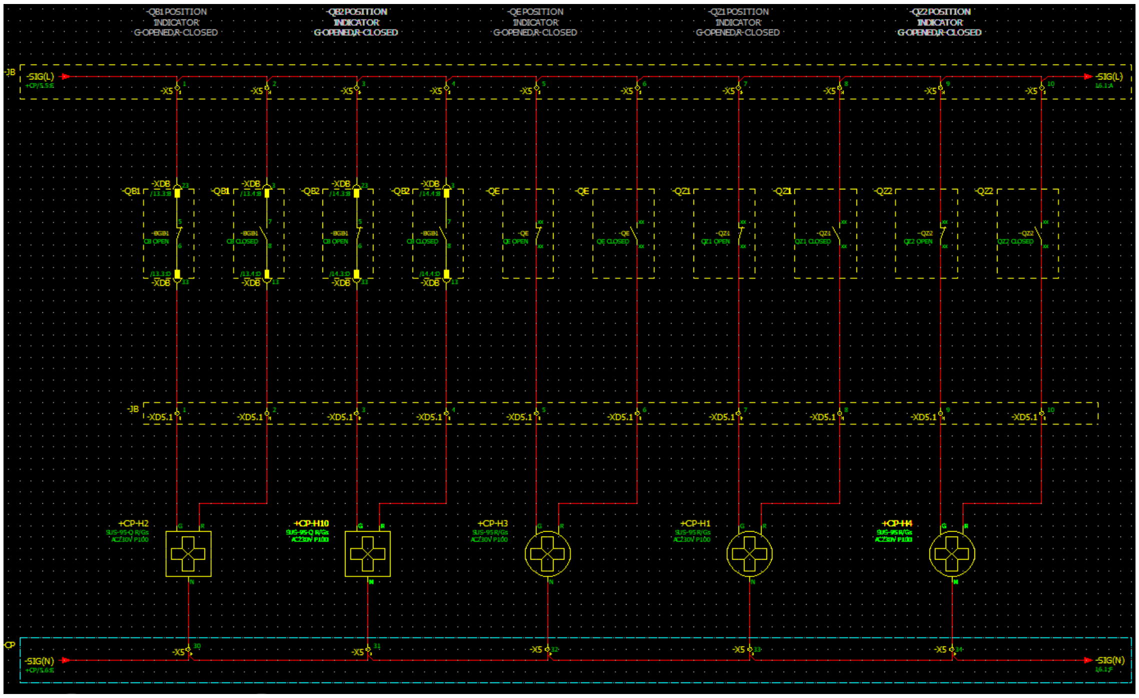

Figure 34 – Example of graphical implementation of the signal circuits

<u>6.5.5 Spring-charge circuits</u>

A motor is used to charge (compress) the close spring. A hook latch keeps the spring charged after the motor stops. When the close command is given, the close coil releases the hook latch, allowing the spring to quickly force the main contacts together. At the same time, the movement of the mechanism compresses the trip spring (the close spring is stronger and can compress the trip spring). A separate hook latch holds the trip spring charged. Once the breaker is closed, the charging motor re-compresses the close spring to be ready for the next closing operation. A trip command will cause the trip coil to release the hook latch on the trip spring, forcing the contacts open.

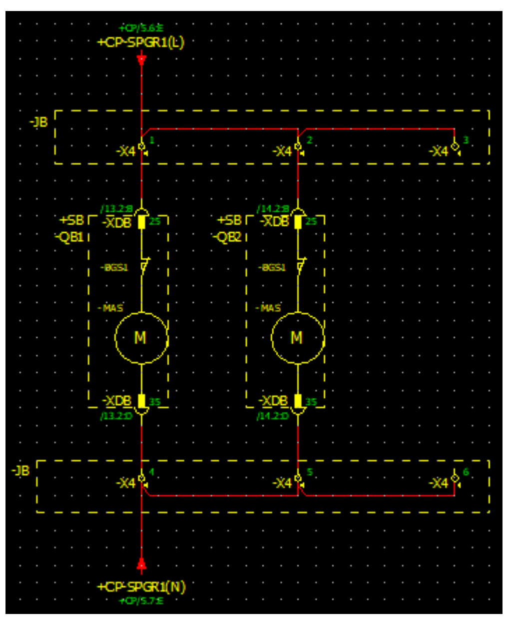

Figure 35 – Example of graphical implementation of the motor spring-charge circuits

6.5.6 Voltage metering circuits

Voltage metering circuits are designed to monitor the voltage level at the terminals of the secondary windings of voltage measuring transformers, which are connected to the analog outputs of the IED through the miniature circuit breaker. On the picture below there is an example of voltage metering circuits for the 35 kV voltage measuring transformers. Those VT’s are hooked not only to the REU615, but also to the RET620 in purpose of additional protection.

During the design of voltage metering circuits, it was discovered that it was not possible to connect both bus bar systems for voltage measurement at the same time because of the absence of the sufficient quantity of the analog outputs in IEDs, so it was decided to use auxiliary relays that would close their the contacts depending on which of the disconnectors was energized and to which busbar it is connected. Graphical representation of this solution can be seen in the Annex D.

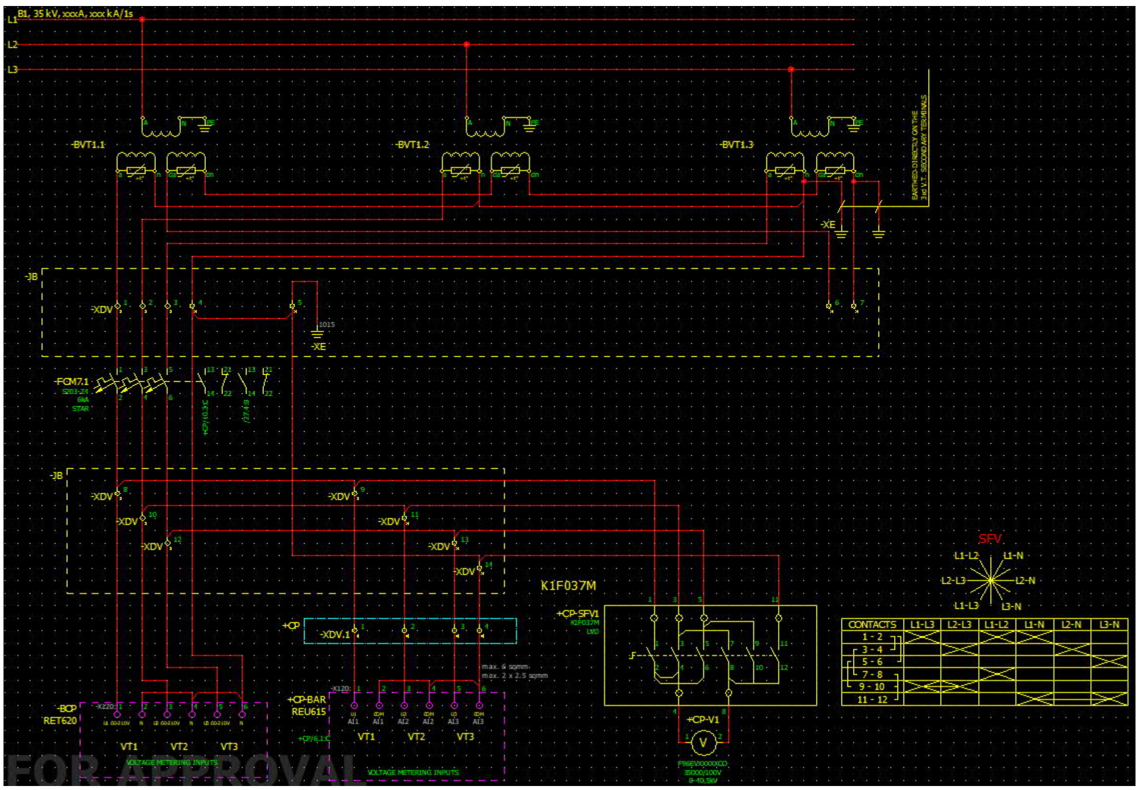

Figure 36 – Example of graphical implementation of the voltage metering circuits

6.5.7 Current metering circuits

Current metering circuits are designed to monitor the current level at the terminals of the secondary windings of current measuring transformers, which are connected to the analog inputs of the IED.

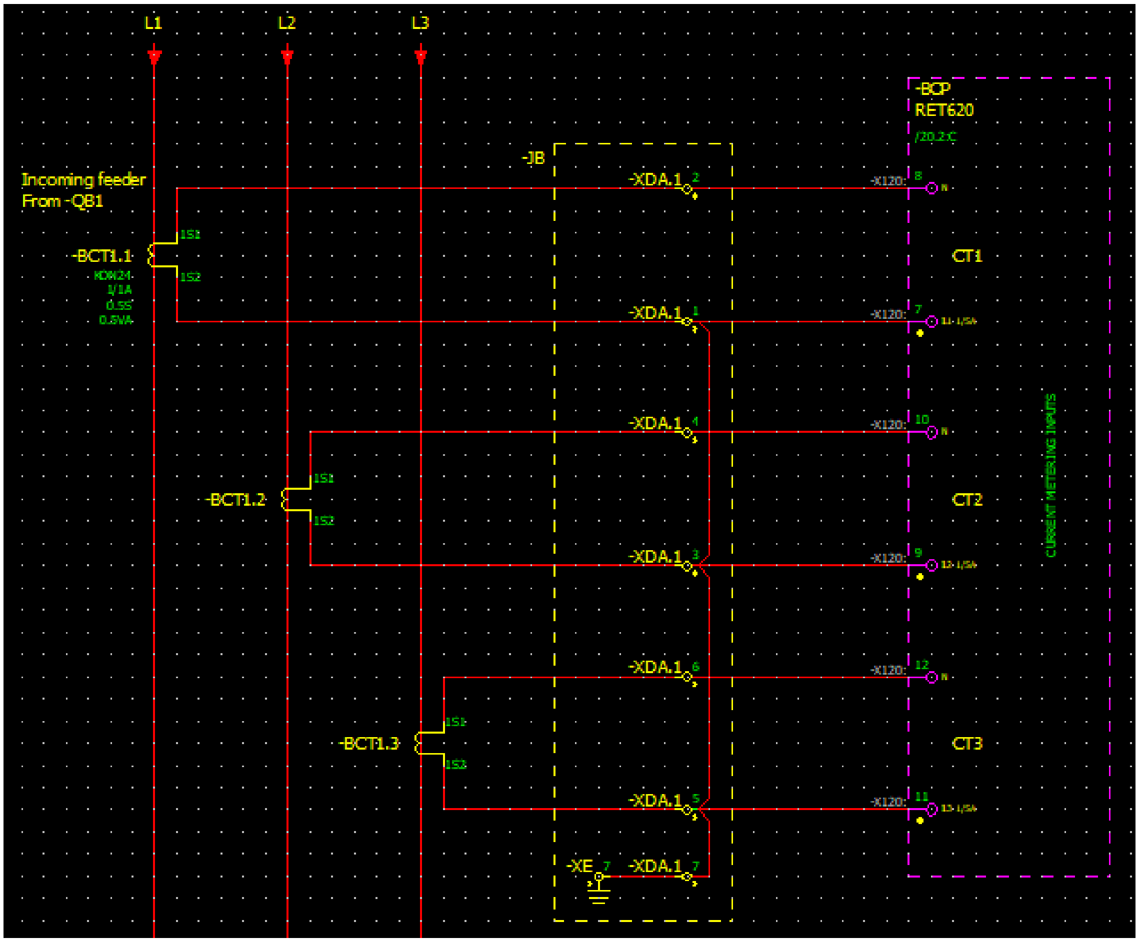

Figure 37 – Example of graphical implementation of the current metering circuits

Conclusion

In the process of performing this thesis, a number of important results were obtained. The main principles of the design process were defined, which laid the basement for the further steps, such as choosing and justification of the busbar arrangement and selection of the primary electrical equipment. At subsequent stages there were defined basic principles of protection that shall be considered during design procedure.

After the creation of the technical specification of the designed substation, the layout concept and 3D model of the substation were created. The calculations of the short-circuit currents were implemented for the purpose of checking if the designed substation meets the standard in the field of electrical power engineering regarding main electrical equipment.

At the final stage, the main attention was paid to the detailed design of the control cabinet for the designed substation, the concept of interlocks, the layout of the front panel, as well as the design of all secondary circuits were completely executed.

Thus, this work reflects the main aspects of the detailed substation design procedure. It is worth to noting that many aspects were not yet designed at the time of writing of this thesis, so it is necessary to consider the possibility of future development of this topic, especially in the field of substation relay protection and relay programming.

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